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STUDIES OF WATER ENTRY

EFFECT OF ATMOSPHERIC PRESSURE ON ENTRY BEHAVIOR OF MODELS OF MARK 13-6 TORPEDO WITH STANDARD HEAD (HEAD F) AND ONE FINER HEAD (HEAD I)

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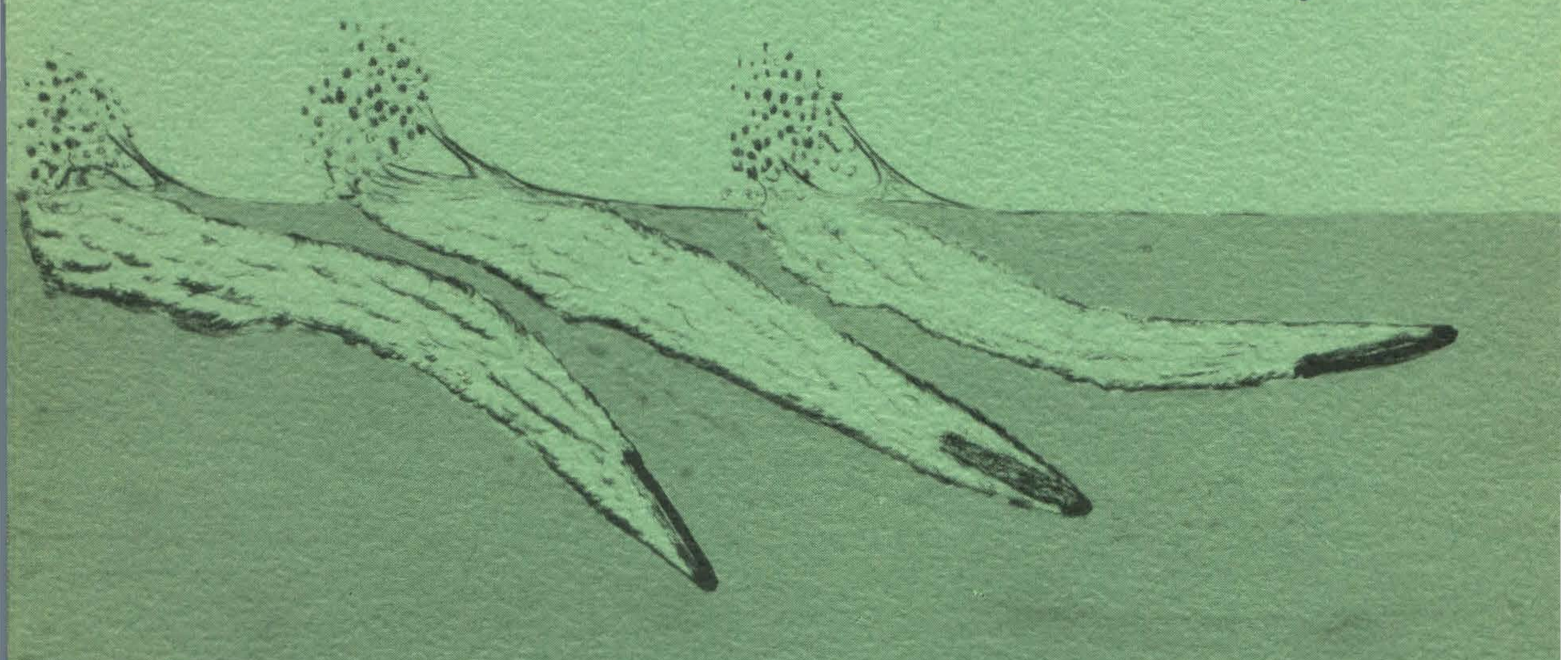

HYDRODYNAMICS LABORATORY

California Institute of Technology

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EFFECT OF ATMOSPHERIC PRESSURE ON ENTRY BEHAVIOR OF MODELS OF MARK 13-6 TORPEDO WITH STANDARD HEAD (HEAD F) AND ONE FINER HEAD (HEAD I)

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ABSTRACT AND CONCLUSIONS

Water entry tests of 2-inch diameter models of the MK 13-6 Torpedo with two nose shapes were made in the Controlled Atmosphere Launching Tank to determine:

a. The effect of atmospheric pressure on the water entry behavior of small models.

b. The influence of nose shape on the magnitude of atmospheric pressure effects.

c. Whether model behavior will be similar to prototype behavior when the speed is scaled according to the Froude law and atmospheric pressure according to the linear scale, and atmospheric density is allowed to vary with the pressure.

Most of the tests were made with a model equipped with Head I, which is a finer shape than the standard head. The tests with this model were made with an entry speed of 119.5 ft. per sec., corresponding to a Froude-scaled prototype velocity of 400 ft. per sec., and with air pressures of 1, 3/4, 1/2, 1/4, 1/11, and 1/22 atmosphere. Two sets of initial angles were used: (a) trajectory 19° and 0° pitch; (b) trajectory 20° and 1.5° flat pitch.

Six tests were made with the standard MK 13-6 head (Head F) with an entry speed of 103 ft. per sec. (prototype speed 343 ft. per sec.), entry trajectory angle 19°, pitch angle 0.8° flat, and air pressures of 1, 1/2 and 1/22 atmosphere. The test results lead to the following conclusions for the range of conditions of these tests:

1. The water entry behavior of a small, slender, fine-nosed projectile, the 2-inch model of the Mark 13-6 Torpedo with Head I, is very sensitive to variations in atmospheric pressure. The average trajectory of the projectile changes consistently in one direction with variation in atmospheric pressure, from a sharply curved diving trajectory at one atmosphere to an upturning trajectory resulting in a broach at an air pressure of 1/22 atmosphere, as shown in Figure 7.

2. The magnitude and character of the influence of atmospheric pressure on the water entry behavior of these projectiles are functions of the nose shape of the projectile. The rather small change in nose shape from Head I to the somewhat blunter hemisphere and cone of the standard Mark 13-6 Torpedo nose (Head F) makes the difference between great sensitivity to atmospheric pressure and virtual insensitivity. Furthermore, what little sensitivity to atmospheric pressure is demonstrated by Head F is different in character from that shown by Head I. The trajectory of Head F moves downward with decrease in atmospheric pressure but reverses its direction and moves upward with further decrease in pressure, whereas the average Head I trajectory moves upward consistently. Compare Figures 7 and 18.

3. Froude scaling of the entry speed and pressure scaling according to the linear scale produces a model trajectory similar to the prototype trajectory. Similitude between model and prototype performance is obtainable even though the atmospheric density is not scaled in accord with general theoretical requirements. See Figure 8.

4. The test projectiles are relatively insensitive to small variations in entry and pitch angles.

5. There are considerable differences in trajectories resulting from repeated launchings with Head I under identical conditions at the high atmospheric pressures of 1 to 1/2 atmosphere. However, similar initial conditions produce similar trajectories at the lower pressures of 1/4 atmosphere and less.

EFFECT OF ATMOSPHERIC PRESSURE ON ENTRY BEHAVIOR OF MODELS OF MARK 13-6 TORPEDO WITH STANDARD HEAD (HEAD F) AND ONE FINER HEAD (HEAD I)

INTRODUCTION

This report covers the first group of a series of tests to be made in the Controlled Atmosphere Launching Tank to determine the effect of atmospheric pressure on the water entry behavior of small air-launched projectiles.

Most of the tests were made with 2-inch diameter models of the MK 13-6 Torpedo equipped with Head I (also called the Dunn nose) which is a finer shape than the spherical-tip and cone head (Head F) of the standard MK 13-6. This shape was selected for the initial study because other experimenters have found that, when launched in open tanks (i.e., where atmospheric pressure was not controlled), small models of this shape behaved quite differently from the prototype. Several tests were made with a model of this torpedo equipped with the standard head, and are included herein for comparison. The diameter of the prototype is 22.42 inches. The models, therefore, are made to a linear scale of 1:11.21.

In studying the behavior of free-flying bodies by means of scale models, the aim is to so control the variables which affect the motion that the model will follow a path which is geometrically similar to that of the prototype it represents, and that the scale ratio of the two paths be the same as the ratio between the linear dimensions of the model and of the prototype.

In model studies of water entry of the MK 13-6 Torpedo at an entry angle of 19°, Mason and Slichter[(1)*] found that with the standard nose shape (Head F) there was fair agreement between model and prototype behavior. However, when a finer shaped head (Head I) was substituted for the spherical-tipped nose, the one-inch diameter models followed a down-turning trajectory which resulted in a deep dive, while the prototype had an upturning trajectory and recovered from the dive.

This anomalous behavior of the model with the fine nose was traced to the shape of the entry cavity on the underside of the nose and to the force distribution which resulted. At model dimensions, the separation between cavity wall and model on the underside of the nose was very narrow. The water in the cavity wall, due to its high-speed motion, pumped the air out of this space and caused an under-pressure which resulted in a downward force on the nose. At prototype dimensions, the clearance was large enough to permit flow of air around the nose so that the pressures on the upper and lower sides of the nose were equalized to some extent. This analysis was verified by providing air inflow through the model to the underside of the nose by perforating the model aft of the nose tip. This produced an upturning trajectory. In the case of blunter noses

* Figures in parentheses refer to bibliography on page 33 of this report

(such as the MK 13-6 standard nose), the angle between cavity wall and projectile is large enough so that even in model size the effect of under-pressure is negligible.

Analysis shows that in model studies of water entry the atmospheric pressure should be reduced in proportion to the linear scale of the models. When such tests are made at full atmospheric pressure, it is possible for pressure differences to develop around the model that are out of proportion with any pressures that could possibly occur in the case of the prototype. For instance, in the case of the model it is possible to develop under-pressures in the cavity which, when translated to prototype scale, would correspond to pressures below absolute zero.

The tests reported herein were made to determine:

a. The influence of atmospheric pressure on model entry behavior.

b. Whether prototype behavior can be paralleled by model behavior when Froude scaling of speed is used and the atmospheric pressure is scaled according to the length scale and the atmospheric density is permitted to vary with the pressure.

FACTORS CONTROLLING WATER ENTRY PHENOMENA

General

Upon entering the water, the projectile opens a cavity in the water and, at first, makes the contact with the water only at the nose. Later on, an elongated projectile may so orient itself in the cavity that its after-part is in contact with the cavity wall. The hydrodynamic forces on the projectile during the latter stage are such as to cause the trajectory to curve so that it is convex toward the side where the tail contacts the cavity wall. The magnitude of these forces and, consequently, the curvature of the trajectory depends, among other things, on the orientation of the projectile in the cavity. The orientation which the projectile can assume within the cavity during this two-zone contact stage is obviously a function of the size and shape of the cavity. Therefore, the shape and size of the cavity and the orientation of the projectile within the cavity are important factors in determining entry behavior.

Froude Similarity Law

In hydrodynamic phenomena involving a free liquid surface, the forces of major importance are usually those of inertia and gravity, since the force of gravity tends to hold the surface level and any distortions of the surface are propagated by inertial forces. The surface phenomena occurring at water entry are in this class, to which Froude scaling applies. That is, two geometrically similar systems will also be dynamically similar if the value of Froude's number is the same in both cases. The Froude number is used in two forms

$$F = \frac{\rho V^2}{\ell\gamma} = \frac{V^2}{\ell\gamma/\rho} = \frac{V^2}{g\ell} \qquad [1a]$$

or

$$F = \frac{V}{\sqrt{\ell\gamma/\rho}} = \frac{V}{\sqrt{g\ell}} \qquad [1b]$$

where, in any consistent system of units,

V = velocity
ℓ = a characteristic length
γ = specific weight of the liquid
ρ = density of the liquid
g = acceleration of gravity

In the first form Froude's number represents the ratio of inertia forces to gravity forces. In the second form it represents the ratio of the velocity V under consideration to the velocity of a shallow water gravity wave in water of depth ℓ. Since surface waves are among the important phenomena in this field, the second form will be used, i.e., $F = V/\sqrt{g\ell}$.

Since the earth's gravitational field is constant over moderate latitudes, the acceleration of gravity is the same for model and prototype. Froude similarity requires, therefore, that the velocity of the model be scaled in proportion with the square root of the linear dimensions, i.e.,

$$\frac{V_m}{V_p} = \sqrt{\frac{\ell_m}{\ell_p}} = \sqrt{\lambda} \qquad [2]$$

where the subscripts m and p refer to model and prototype, respectively, and λ is the linear scale ratio.

Scaling of Atmospheric Pressure

Several different approaches may be used in arriving at the law governing the scaling of atmospheric pressure in model entry studies. Two of these will be given here, one based on a consideration of static pressures and one based on dynamic similarity.

During the high-speed entry of projectiles, gas-filled cavities are carried into the water. The volumetric behavior of these cavities depends on the absolute pressure in the liquid surrounding them. Now, the absolute pressure at any point within the liquid consists of both the static head of liquid above that point and the atmospheric pressure superimposed on the surface. Because of the scale ratio of the two systems, it is obvious that,at any point in the model system. the liquid pressure is reduced from that of the corresponding point in the prototype system in the same ratio as the linear dimensions. In order to make the absolute pressures have the same ratio, it is necessary to reduce the atmospheric pressure also to the same scale as the linear dimensions.

The shape and size of the entrance cavity are determined by the shape of the nose of the projectile, the orientation of the projectile in the cavity, and by the value of the cavitation parameter(2), which is defined as

$$K = \frac{P_L - P_B}{\frac{1}{2}\rho V^2} \qquad [3]$$

in which, using any consistent system of units

P_L = absolute static pressure in the undisturbed liquid

P_B = absolute gas pressure within the cavity

V = velocity of the projectile

ρ = density of the liquid

The cavitation parameter K is proportional to the ratio of the static pressure difference (P_L-P_B), tending to collapse the cavity, to the inertia forces tending to open the cavity. The latter forces are proportional to the dynamic pressure $\frac{1}{2}\rho V^2$.

The cavity surrounding the model will be similar to that surrounding the prototype if the cavitation parameter K has the same value in both cases.

As already shown, the Froude law demands that the velocity of the model be reduced in proportion to the square root of the linear scale. The dynamic pressure $\frac{1}{2}\rho V^2$ of the model system, therefore, is reduced in direct proportion with the linear scale when, as is generally the case, the same liquid is used for both model and prototype studies. In order to have the same value of K in the case of the model as the prototype, it is also necessary to reduce the static pressure $(P_L - P_B)$ in proportion with the linear dimensions. If the absolute pressure within the cavity, P_B, is negligibly small, it remains only to scale the absolute liquid pressure, and, as shown before, this necessitates the scaling of atmospheric pressure in proportion to the linear dimensions.

It should be noted here that as long as the cavity is wide open and the gas pressure within the cavity is substantially equal to that of the atmosphere above the water, the atmospheric pressure does not affect the behavior of either the cavity or the projectile. In that case the value of $(P_L - P_B)$ is independent of atmospheric pressure and is equal to the static head of liquid. Under these conditions similitude of entry behavior may be obtained by proper scaling of the velocity alone. When the cavity pressure is neither equal to atmospheric pressure nor negligibly small, it is necessary that both atmospheric pressure and cavity pressure be scaled from those of the prototype in proportion to the linear dimensions.

Scaling of Atmospheric Density

In the preceding paragraphs only the pressure of the atmosphere was discussed. If air is used in model tests, the density of the atmosphere varies directly with the absolute pressure. In some cases, however, it is necessary to control the density of the atmosphere independently of the pressure, which necessitates the use of gases other than air.

The density of the atmosphere above the water was shown to be of importance in the vertical entry of spheres. Davies[3] studied entry phenomena by dropping small spheres and projectiles into nitrobenzene at different atmospheric pressures. The entry velocities were of the order of 20 ft. per sec. and the maximum projectile diameter was 5/8 inch. Since an air atmosphere was used, the density varied directly with the absolute pressure. The investigation showed that the time of surface closure increases as the surface pressure decreases.

Gilbarg and Anderson[4] shot spheres and cylinders vertically into the water and observed the phenomena at different atmospheric pressures. They also experimented with a freon-air mixture at reduced pressure but the same density as air at normal atmospheric pressure. The spheres ranged in size from 1/4-inch to 1-inch diameter and the velocities to about 100 ft. per sec. They concluded that (a) Froude's law is adequate for scaling air-water entry cavities when surface closure occurs late or not at all; (b) surface sealing is the factor most responsible for non-Froude scaling of cavity phenomena; and (c) surface sealing depends chiefly upon atmospheric density and projectile velocity.

It is seen that the density of the gas is important mainly through its effect on the time and location of the cavity closure. The subsequent behavior of the cavity and the projectile are affected thereby, since the behavior of the closed cavity is affected significantly by its volume at closure. This is important in the case of the vertical entry of spheres, since surface closure occurs early and bubble growth continues for some time thereafter. Theory indicates that in a case like this, good similarity will be obtained by reducing atmospheric pressure in proportion to linear dimensions, but leaving the density equal to the density of air at full atmospheric pressure, i.e., by using an atmosphere of a heavy gas [5]. This can be shown as follows:

Surface closure, i.e., the folding-in of the water in the splash to form a dome which completely closes off the cavity at the surface, is due to the dynamic forces exerted on the water by atmospheric gas rushing into the cavity. For reasons stated before, Froude scaling is used in model studies and linear dimensions are scaled as λ, velocities as $\lambda^{\frac{1}{2}}$, times as $\lambda^{\frac{1}{2}}$, accelerations as λ^{0} or 1, and forces (if the density of the liquid is the same for model and prototype) are scaled as λ^3. The first two ratios were derived before and the remainder follow from them using the relations of simple mechanics. The atmospheric density to be used with the model can then be determined from the requirement that the dynamic gas forces be scaled as the cube of the linear dimensions, or $F_m/F_p = \lambda^3$

but $$F_m = \frac{1}{2}\rho_m V_m^2 \ell_m^2 = \frac{1}{2}\rho_m (V_p^2 \lambda)(\ell_p^2 \lambda^2) = \frac{1}{2}\rho_m V_p^2 \ell_p^2 \lambda^3$$

and $$F_p = \frac{1}{2}\rho_p V_p^2 \ell_p^2$$

$$\frac{F_m}{F_p} = \lambda^3 = \frac{\frac{1}{2}\rho_m V_p^2 \ell_p^2 \lambda^3}{\frac{1}{2}\rho_p V_p^2 \ell_p^2} = \frac{\rho_m}{\rho_p}\lambda^3$$

therefore $$\frac{\rho_m}{\rho_p} = 1$$

In the above expressions, ρ and V refer to the density and velocity of the atmospheric gas, and the subscripts m and p refer to model and prototype, respectively.

The experiments with spheres entering water vertically, referred to above, showed that the density of the atmosphere is important in determining time of surface closure and, therefore, the subsequent behavior of bubble and projectile. These experiments showed also that surface closure occurs almost only when the splash rises symmetrically. When the surface was ruffled very slightly by droplets of water preceding the entry of the sphere, the splash was badly malformed and did not close under conditions for which it would have closed normally (Reference 4, Paragraph 16). This leads to the belief that in oblique entry of projectiles, where the splash is far from being symmetrical, surface closure may not occur at all. The density of the atmosphere may, therefore, be relatively unimportant in determining the behavior of projectiles entering obliquely.

Scaling of Underpressure in Throttled Cavity

In some cases of water entry the cavity remains open to the atmosphere for an appreciable length of time after entry. The cavity at some distance behind the projectile may then neck down and throttle the flow of gas into the cavity. It was shown before that to obtain a model cavity that is geometrically similar to the prototype cavity, it is necessary that the difference between the static liquid pressure and the cavity pressure, $P_L - P_B$, be scaled in the same ratio as the linear dimensions. If the pressure within the cavity P_B differs appreciably from atmospheric pressure P_A, it is necessary that the pressure drop between atmosphere and cavity, $P_A - P_B$, also be scaled as the linear dimensions. That this case also requires an atmospheric density ratio of one to one between model and prototype is shown as follows:

Writing Bernoulli's equation for flow of gas into the cavity, we have

$$P_A + 0 = P_B + \frac{1}{2}\rho\ V^2$$

or

$$(P_A - P_B) = \frac{1}{2}\rho\ V^2$$

$$\frac{(P_A - P_B)_m}{(P_A - P_B)_p} = \lambda = \frac{\frac{1}{2}\rho_m V_m{}^2}{\frac{1}{2}\rho_p V_p{}^2} = \frac{\rho_m V_p{}^2\lambda}{\rho_p V_p{}^2} = \frac{\rho_m}{\rho_p}\lambda$$

therefore

$$\frac{\rho_m}{\rho_p} = 1$$

This consideration, however, could not be important in studies using small scale models with correctly scaled atmospheric pressure, since the total atmospheric pressure is small and any differences between that and cavity pressure due to throttling would be of second order.

Scaling of Vapor Pressure

As the projectile progresses along its path during the cavity stage, the cavity finally closes behind it. Gas within the cavity is pumped away be entrainment in the turbulent wake. The projectile may then shed the cavity entirely, or, if the velocity is still high enough and the submergence sufficiently low, there may be a transition into a stage of pure cavitation. The bubble surrounding the projectile would then be filled with water vapor and the pressure within the cavity would be that of saturated vapor at the temperature of the ambient water.

It was shown before that one of the requirements for similarity of cavities is that the cavity pressure be scaled in the same ratio as the linear dimensions. To maintain strict similarity during the stage of pure cavitation it would be necessary, therefore, to adjust the vapor pressure. Since water is used in most model experiments, this requirement is difficult to attain. If the water were to be chilled nearly to the freezing point, the vapor pressure would be reduced only to about one-third its value under normal atmospheric conditions, which would correspond to a model scale of one-third and no smaller.

However, the water vapor pressure is probably not important in most cases since, for pure cavitation, the gas pressures are very small as compared to the liquid dynamic pressures and, therefore, a manifold change in the gas pressure would have little effect on the force system.

Scaling of Viscous Forces

The viscosity forces become appreciable only after the cavity has been shed and the projectile is completely wetted by the liquid. To maintain similarity of viscous forces during this stage it would be necessary to satisfy Reynolds criterion, i.e., the Reynolds number of the model should equal that of the prototype. Reynolds number is defined as

$$R = \frac{V\ell}{\mu/\rho} = \frac{V\ell}{\nu}$$

in which, using any consistent system of units,

V = velocity
ℓ = characteristic length
μ = absolute viscosity of liquid
ρ = density of liquid
ν = kinematic viscosity of liquid

Where the same liquid is used for model and prototype (same viscosity), this requires that the velocity be scaled as the inverse ratio of the linear dimensions, or as λ^{-1}. Froude scaling, however, requires that velocity be scaled as $\lambda^{1/2}$. It is obvious therefore, that both requirements cannot be satisfied simultaneously if water is used in model experiments. To satisfy both conditions, the viscosity of the liquid in model tests would have to be scaled from that of the prototype as $\lambda^{3/2}$. That is, for a linear scale ratio of 1/10, the viscosity ratio would have to be approximately 1/32.

In experiments conducted at low Reynolds numbers, therefore, one should not expect similarity beyond the cavity stage. However, at Reynolds numbers considerably above one million (based on projectile length), geometric similarity may be good although the time scale will be off. Wind tunnel and water tunnel tests show that the lift and moment acting on submerged bodies are very nearly independent of the Reynolds number when this is well above 10^6. Geometric similarity of trajectories may be expected, therefore, even though viscous effects are not scaled. The drag, on the other hand, is still a function of the Reynolds number, and would cause higher decelerations in the model during the last stage when it is completely wetted.

Scaling of Surface Tension

Surface tension forces may be appreciable in tests made to a very small scale and very low velocity. With larger scale and higher velocity, and especially where surface seal does not occur, surface tension forces are completely negligible by comparison with those of inertia and gravity. For instance, for a one-inch diameter projectile entering with a velocity as low as 20 fps, the inertia forces of the water are several hundred times greater than the surface tension forces. Therefore, the formation of the cavity would be independent of surface tension. On the other hand, the inertia forces of the atmospheric gas are of the same order of magnitude as the surface tension forces. Surface seal, therefore, would be affected by surface tension.

TEST CONDITIONS

Apparatus

The launchings were made in the Controlled Atmosphere Launching Tank (described briefly in Appendix I; full description in Reference 6). The tank provides control of trajectory angle, pitch angle, launching velocity and atmospheric pressure. A rubber diaphragm near the tank bottom is used to absorb the model's energy. Photographs were taken of the model during launchings at the rate of 500 per second through water which was originally distilled and whose clarity has been maintained by filtering.

Models

Models of the Mark 13-6 Torpedo were used as test projectiles. Head I (also known as the Dunn nose), which is a finer shape than the spherical-tip and cone nose (Head F) of the standard Mark 13-6, was selected for the major portions of these tests because large discrepancies had been found between prototype behavior and the behavior of small models when launched at normal atmospheric pressure(1). Head F was chosen for the comparison tests because fair agreement had been found between model and prototype performance at normal atmospheric pressure. In addition, prototype performance data were available for these shapes to use in comparing model and prototype entry behavior. Three duplicate models with Head I and one with Head F were used in these tests.

All models used were two inches in diameter, geometrically and dynamically scaled from the 22.42-inch diameter MK 13-6 Torpedo "floater" version used at Morris Dam. The floating version was selected for full-scale tests at Morris Dam because it greatly simplified recovery of the missiles from the lake. Model experimenters then adopted this version so model tests could be correlated with full-scale tests, and this version became known as the "correlation model." The specifications and tolerances for correlation models of various sizes are given in Appendix II. All four models used in these tests meet the specifications for correlation studies. Their characteristics are given below:

Head Shape	I	I	I	F
Model	A2C2N2	A2C2N1	A5C5N3	A3C1N1
Length, inches	14.133	14.125	14.120	14.128
Diameter, inches	2.001	2.002	2.002	2.001
Distance of CG from nose, inches	6.226	6.159	6.220	6.160
Weight, lb	1.069	1.072	1.086	1.092
Moment of inertia, lb. ft^2	0.1474	0.1471	0.1463	0.1445

The contours of the heads and afterbodies of these models were held to the ± 0.002-inch tolerance prescribed for the diameter. The sections themselves were machined slightly undersized to allow for the coat of paint which is about 0.002 inch thick.

The models are made of duraluminum except for the 2-inch center section, which is of stainless steel. This center section is grooved for fastening in the launching chuck. The groove should have no effect on the trajectory during the cavity stage, although it may have some effect after the cavity has been detached. The model, except for the center section, is covered with a light coat of white lacquer to produce a satisfactory image on the film. Figures 1 and 2 show the outlines of either model or prototype (dimensions given in terms of calibers) with Head I and with Head F,

$$R = b + \frac{8}{3}\sqrt{\frac{b}{K}}\left(\sqrt{Kb-L} - \sqrt{Kb} + \frac{L}{2\sqrt{Kb}} + \frac{L^2}{8(Kb)^{3/2}}\right)$$

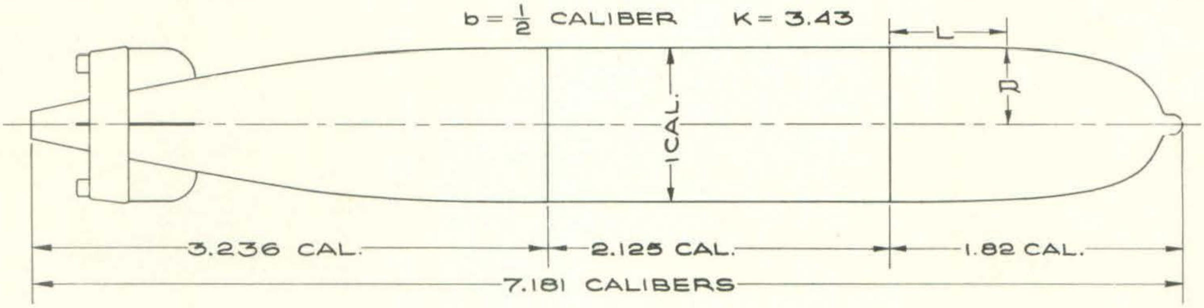


FIG. 1 - OUTLINE OF MK 13-6 TORPEDO WITH HEAD I

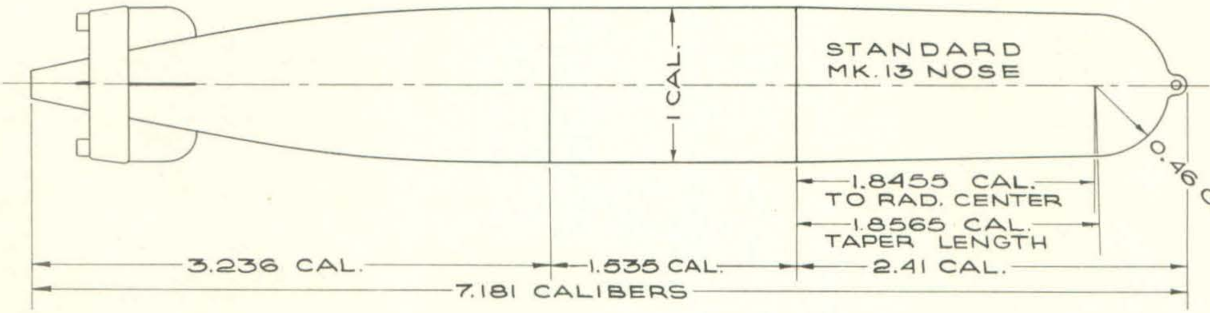


FIG. 2 - OUTLINE OF MK 13-6 TORPEDO WITH HEAD F

respectively. Figure 3 shows a comparison of the outline of Head I with that of the standard MK 13-6 Head F. Figures 4 and 5 are photographs of the two models. The stainless steel center section and fastening groove are shown plainly in the pictures. Figure 6 is a sectional view of a model with Head F, showing internal construction.

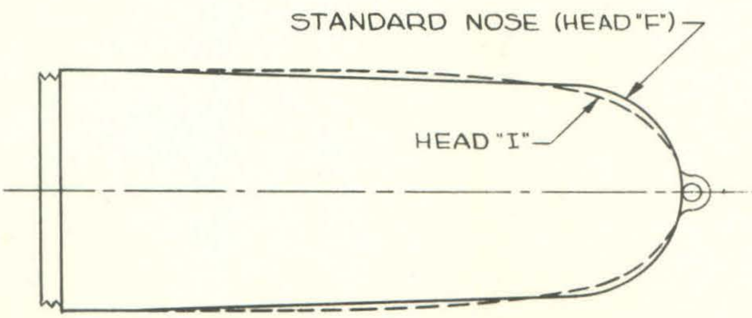


FIG. 3 - COMPARISON OF CONTOURS HEAD I AND HEAD F

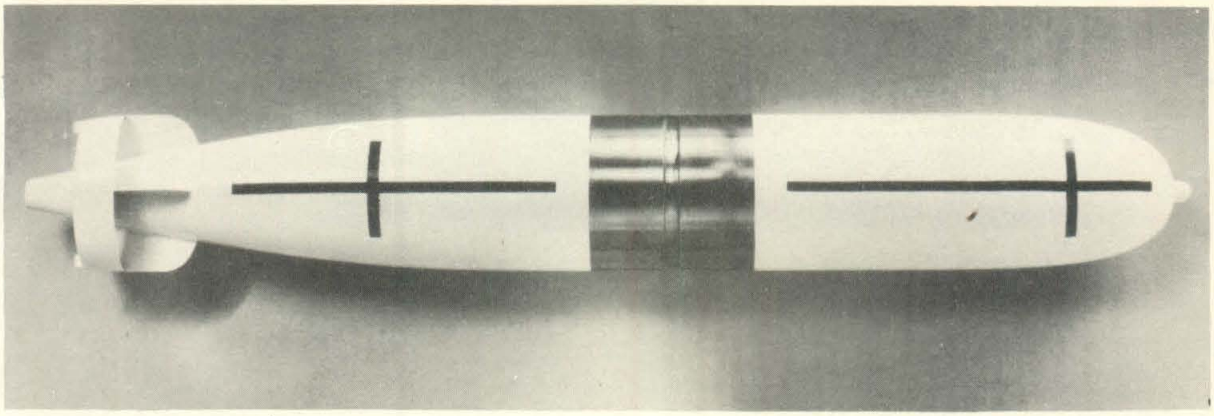


FIG. 4 – MODEL OF MK 13-6 TORPEDO WITH HEAD I

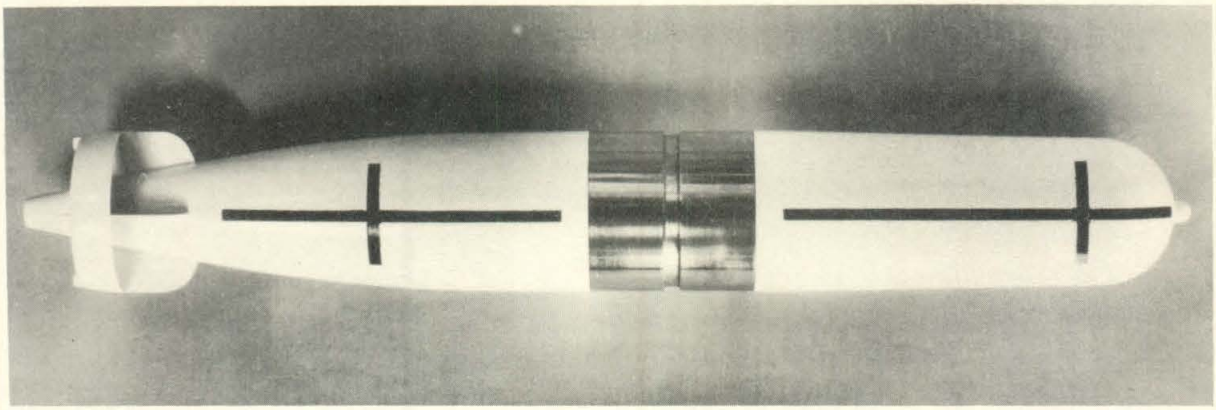


FIG. 5 – MODEL OF MK 13-6 TORPEDO WITH STANDARD HEAD F

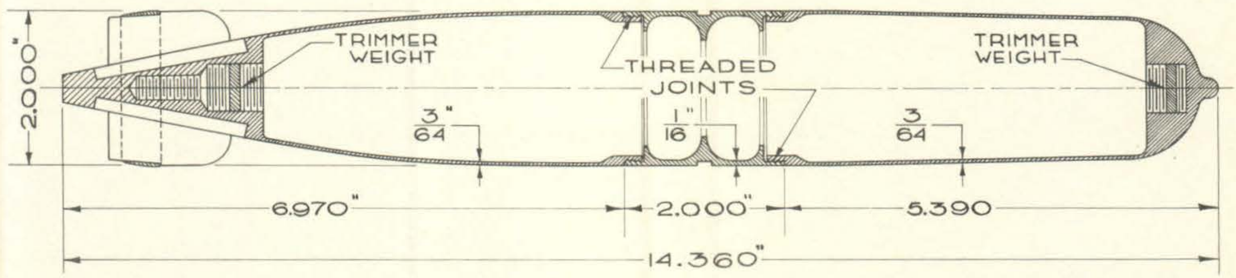


FIG. 6 – SECTIONAL VIEW – MODEL OF MK 13-6 TORPEDO WITH HEAD F

Launching Conditions

The launching conditions for these model tests were chosen to give data for comparison with prototype data obtained by the Morris Dam Group of Naval Ordnance Test Station, Inyokern. Prototype tests were selected for which the Froude-scaled model launching conditions fall within the present operating range of the Controlled Atmosphere Launching Tank. The tests are divided into two groups:

1. Tests with Head I

The entry speed for all tests in this group was set at 119.5 ft. per sec., corresponding to a Froude-scaled prototype velocity of 400 ft. per sec. for a geometrical scale ratio λ of 1/11.21.

The first few tests were made with a trajectory angle of 19° (the inclination of the full-scale launching tube at Morris Dam) and zero pitch. The prototype data which were later obtained showed that, due to deflection of the trajectory during air flight, the actual entry conditions were about 20° trajectory angle and 1.5° flat pitch (nose up with respect to trajectory). The remainder of the tests were set for these angles. The test results showed that the entry angles varied from 19° to 20.8° trajectory, and 0.5° steep to 2° flat pitch, and that these variations in trajectory and pitch angles had little effect on the subsequent behavior of the models.

All launchings were made with an air atmosphere. Tests were made at nominal values of atmospheric pressure of 1, 3/4, 1/2, 1/4, 1/11 and 1/22 atmospheres. The value of 1/22 atmosphere corresponds to the lowest pressure obtainable with the present evacuation equipment. The value of 1/11 atmosphere was selected to correspond to the linear scale of the model. The actual test conditions are presented in Table I.

2. Tests with Head F

The entry speed for the six tests of this group was 103 ft. per sec., corresponding to a Froude-scaled prototype speed of 343 ft. per sec. The entry trajectory angle was 19°, and the pitch angle was 0.8° flat (nose up). All launchings were made with an air atmosphere. Tests were made in pairs at three values of air pressure, with absolute pressures of 1 atmosphere, 1/2 atmosphere, and 1/22 atmosphere.

Analysis of Data

The analysis of the film record was made with the sole purpose of determining the elevation view of the trajectory and the inclination of the model's axis. That is, only the x-and z-coordinates and the model inclination were read, although in some cases there were slight displacements in the y-direction.

The trajectory and pitch angles were set to the nearest 0.1°. The observed values were found to be different from the pre-set values by some tenths of a degree, with a constant tendency toward steeper trajectories combined with nose-up pitch. This indicates that the present model-release mechanism releases the models a few tenths of a degree ahead of the pre-set point.

The experimentally determined trajectory angles are correct to ± 0.2°. The values of inclination, although read to the nearest 0.1°, show some scatter due to envelopment of a portion of the model by the bubble, and indistinct photography. However, not all

TABLE I

Run No.	Model Used	Entry Angles Traj.	Entry Angles Pitch	Tank Atmosphere Pressure In.Hg.Abs.	Tank Atmosphere Pressure Std.Atms.	Entry Velocity ft/sec
10-1	A2C2N2	19.0°	0.3°F*	29.22	0.977	119.5
10-2	"	19.0	0.5 F	29.29	0.979	"
11-1	A2C2N1	19.0	0.2 F	29.25	0.978	"
-3	"	19.3	0.3 F	2.67	0.089	"
-4	"	19.0	0	22.44	0.751	"
-6	"	19.0	0	15.30	0.512	"
-7	"	19.0	0.3 F	29.28	0.979	"
-8	"	19.0	0	29.28	0.979	"
-9	"	19.6	0.6 F	15.28	0.511	"
-10	"	19.2	1.0 F	2.67	0.089	"
-13	"	20.4	0.6 F	2.67	0.089	"
-14	"	20.0	0.1 F	2.67	0.089	"
-16	"	20.8	1.0 F	1.35	0.045	"
-19	"	20.8	1.2 F	1.35	0.045	"
-20	"	19.0	0.5 S**	7.48	0.250	"
-21	"	19.0	0	7.48	0.250	"
-22	"	19.3	0.7 F	22.44	0.751	"
-23	"	20.1	0.5 F	29.25	0.978	"
-24	"	20.1	0.4 F	29.26	0.978	"
-25	"	20.2	2.3 F	29.23	0.977	"
-26	"	20.1	1.7 F	2.67	0.089	"
12-1	ABCBN3	20.1	0	2.67	0.089	"

* F = Flat = Nose up with respect to trajectory
**S = Steep = Nose down with respect to trajectory

of the roughness of the inclination curves is due to scatter of data. The model definitely does bounce up and down as it moves along the trajectory.

Coordinate positions were read to .01 diameter. Here, again, some uncertainties arise due to indistinctness caused by the bubble and other factors, as well as the effect of movement of the model from the launching plane. The readings, nevertheless, are correct to within ± 0.05 diameters in most cases and to ± 0.1 diameter under the worst conditions.

TEST RESULTS

The primary objective in this investigation was to study the over-all effect on projectile behavior of variations in atmospheric pressure. Emphasis is placed, therefore, on the resulting trajectory rather than on details such as whip at entry or orientation of the model within the cavity. The trajectory angle and pitch angle at entry were determined for each launching as a check of the pre-set launching conditions. For the underwater trajectory, the film record was analyzed only for the coordinate position in the vertical plane and inclination of the model. The entry speed was taken as the controlled launching speed.

The discussion of the test results for each of the two shapes tested is presented separately.

Head I

Significant results are observed when the average trajectories at the various pressure conditions are compared, as is done in Figure 7. Analysis of the entry trajectory and pitch angles showed relatively little variation from launching to launching so that these average trajectories are for comparable conditions of entry angle, pitch angle, and speed. Therefore, any differences in these trajectories must be attributed to the other variable, the atmospheric pressure. Thus, the consistent progression from a downward curving, diving trajectory at an air pressure of one atmosphere to the sharply upward curving, broaching trajectory at 1/22 atmosphere represents the effect of the change in tank air pressure alone.

It is then interesting to compare the average model trajectories with an average prototype trajectory for similar entry conditions based on the Froude scaling of velocity, in Figure 8.

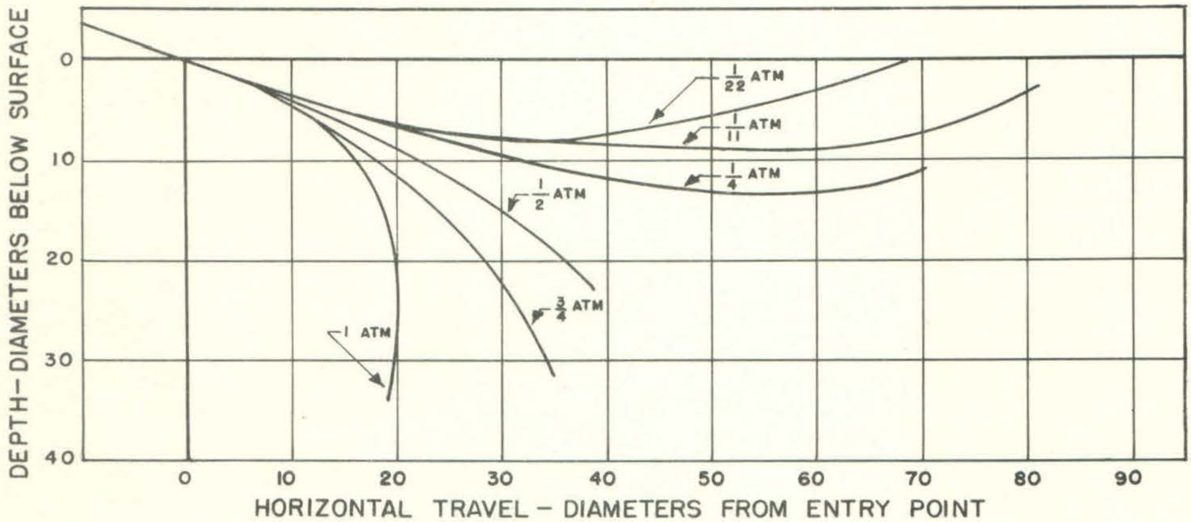


FIG. 7 – MK 13-6 TORPEDO WITH HEAD I
EFFECT OF ATMOSPHERIC PRESSURE ON AVERAGE MODEL TRAJECTORIES

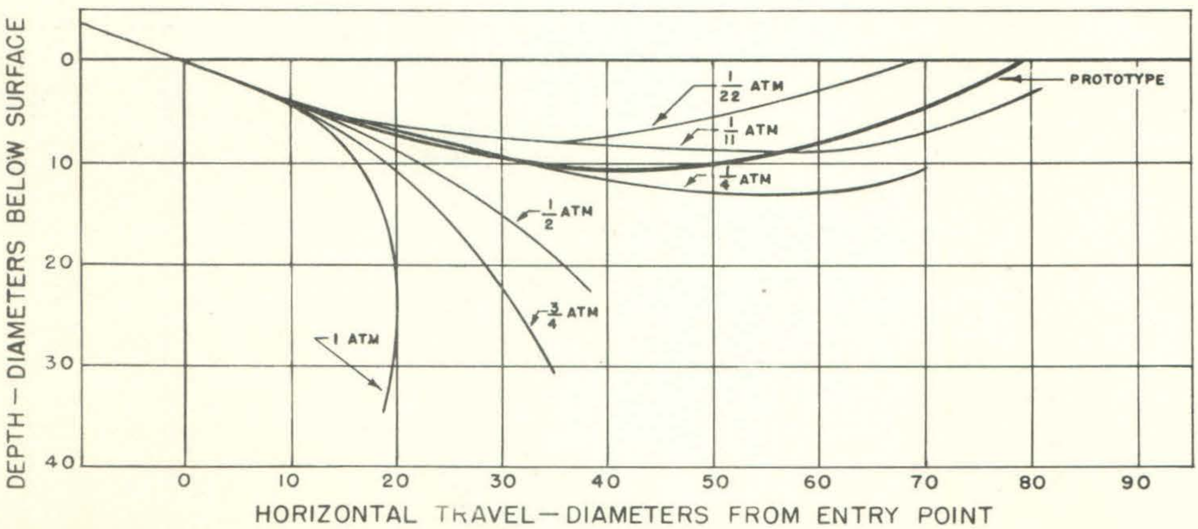


FIG. 8 – MK 13-6 TORPEDO WITH HEAD I
AVERAGE TRAJECTORIES OF MODEL AND PROTOTYPE

Particular attention is directed to a comparison of the average prototype trajectory with the average model trajectory at 1/11 atmosphere. It will be recalled that theoretical considerations show that with the scale ratio used, model launchings should be made with an atmospheric pressure of 1/11 atmosphere. It will be noted that there is closer correspondence between the average model trajectory at 1/11 atmosphere and the prototype trajectory than between any other model trajectory and the prototype trajectory, even though the correspondence is not perfect. It is interesting that the model trajectory lies on different sides of the prototype trajectory at different points, being first above it and then beneath it. Nevertheless, for at least 70 diameters of horizontal travel, the model trajectory corresponds to the prototype trajectory within 2.5 diameters, which is approximately equal to the spread between repeated launchings of both model and prototype. This reasonably close correspondence between scaled model tests and prototype performance has been obtained by scaling of speed according to the Froude law, and the atmospheric pressure according to model scale, without regard to scaling of the atmospheric density, since the air density varied with the pressure.

These results lead to the conclusion that reasonable similtiude between model and prototype trajectories can be obtained in tests of the Mark 13-6 Torpedo with Head I at 19° to 21° trajectory angle, with pitch angles between 0.5° steep and 2°flat, and prototype speed of 400 ft. per sec. by Froude scaling of speed and by scaling the atmospheric pressure according to model scale. However, it seems reasonable to expect that the range of application for this scaling principle should be quite broad. Further work is necessary at different angles, speeds, scale ratios and shapes to determine working limits.

The average model trajectories and envelopes of the test trajectories from which they were derived, are presented as Figure 9. The fact that there is an overlap of data for some of the pressure conditions is evident. On the other hand, the envelope for the 1/4 atmosphere condition is a line despite the fact that two runs are represented. This is the same number of runs as represent the very wide spread at 3/4 atmosphere. The detailed individual trajectories and model inclination curves have been grouped by pressure condition and are presented as Figures 10 through 16, for the pressures of 1, 3/4, 1/2, 1/4, 1/11 and 1/22 atmosphere. Each curve is identified by two

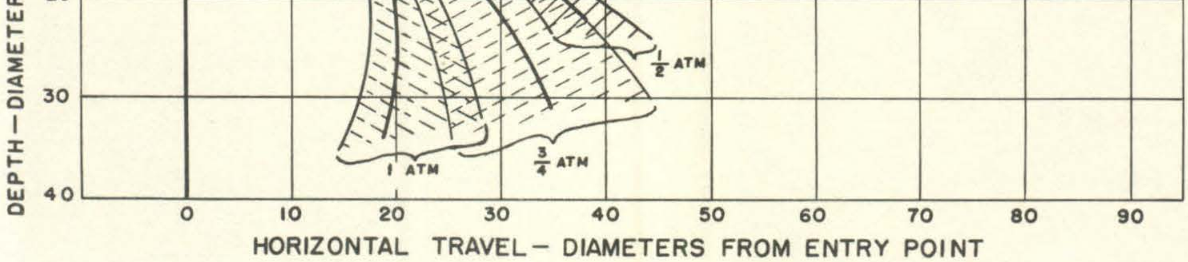


FIG. 9 – MK 13-6 TORPEDO WITH HEAD I
TRAJECTORY ENVELOPES AND AVERAGE TRAJECTORIES

figures. The first gives the measured entry trajectory angle. The second gives the measured entry pitch angle. It will be remembered that all launching speeds were set at 119.5 ft. per sec. Although the trajectories as presented are defined by points, these points are only a fraction of those which could have been obtained from the photographic record had minute analysis of each trajectory been the objective.

In Figure 10, we see that seven of eight launchings at a pressure of 1 atmosphere produced data which fall within a spread of five diameters even at the end of the measured trajectories. On the other hand, one run deviated so far from the others that at the end of its trajectory the model was about 10 diameters from the nearest corresponding trajectory. These launchings were made with two models, there being two runs with one and six runs with the other. The erratic trajectory was the first launching of the model with which the six runs were ultimately made, thus eliminating the possibility of some undetected difference in model shape as a cause of this variation. However, the difference could have been in some surface property of a newly painted model as compared with one subjected to repeated handling. It is interesting to note that one other trajectory which differed from others in its group (trajectory with earliest broach in Figure 14) also resulted from a launching with a newly painted model. This indicates the advisability of investigating the effect of surface finish on model behavior.

This group of launchings represents three nominal launching conditions — 19° and 20° trajectory at 0° pitch, and 20° trajectory with 1-1/2° flat pitch. The actual trajectory and pitch angle data are tabulated below in Table II, in order of decreasing curvature of trajectory, with those for the most curved trajectory first and the least curved one last:

TABLE II

Trajectory Angle	Pitch
19.0°	0.3°F
20.1	0.4 F
19.0	0
20.1	0.5 F
19.0	0.5 F
19.0	0.3 F
20.2	2.3 F
19.0	0.2 F

If only the first seven launchings are considered and the widely deviating trajectory is ignored, it is seen that the spread of the trajectories at the same condition of 19.0° entry trajectory angle and 0.3° flat entry pitch angle includes all trajectories except the extreme one at 20.2° trajectory angle and 2.3° flat pitch, which is excluded only by a fraction of a diameter of horizontal travel. However, even then the maximum spread between these trajectories, at 19.0° trajectory and 0.3° flat pitch, at their ends, is of the order of only 3 diameters.

Because of the relatively small spread of data for the seven tests, it is concluded that small changes in trajectory and/or pitch angle had little effect on the trajectories produced. The reason for the large deviation of the eighth trajectory is yet to be determined.

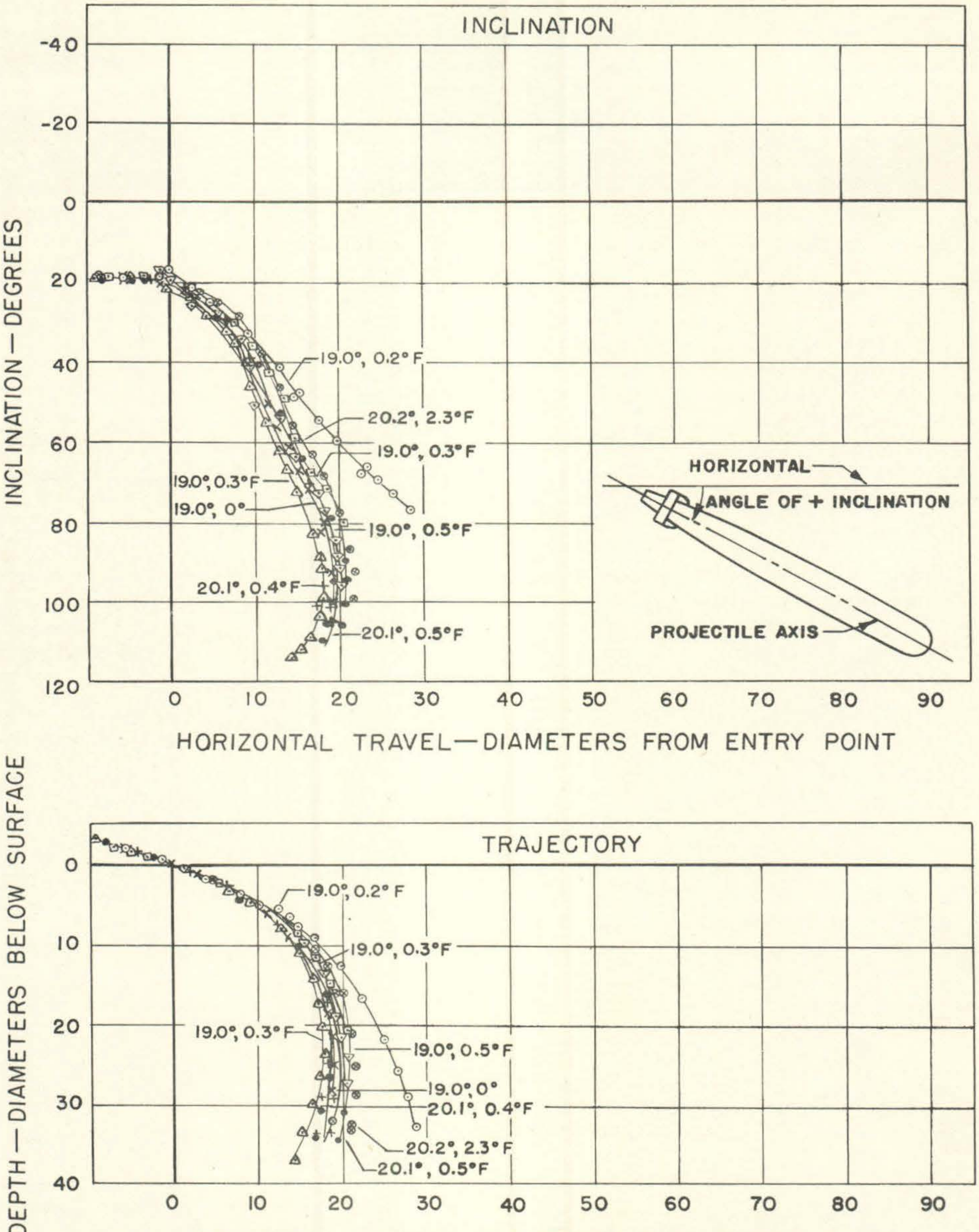


FIG. 10 – MK 13-6 TORPEDO WITH HEAD I
INDIVIDUAL MODEL TRAJECTORY AND INCLINATION CURVE
AIR PRESSURE 1 ATMOSPHERE

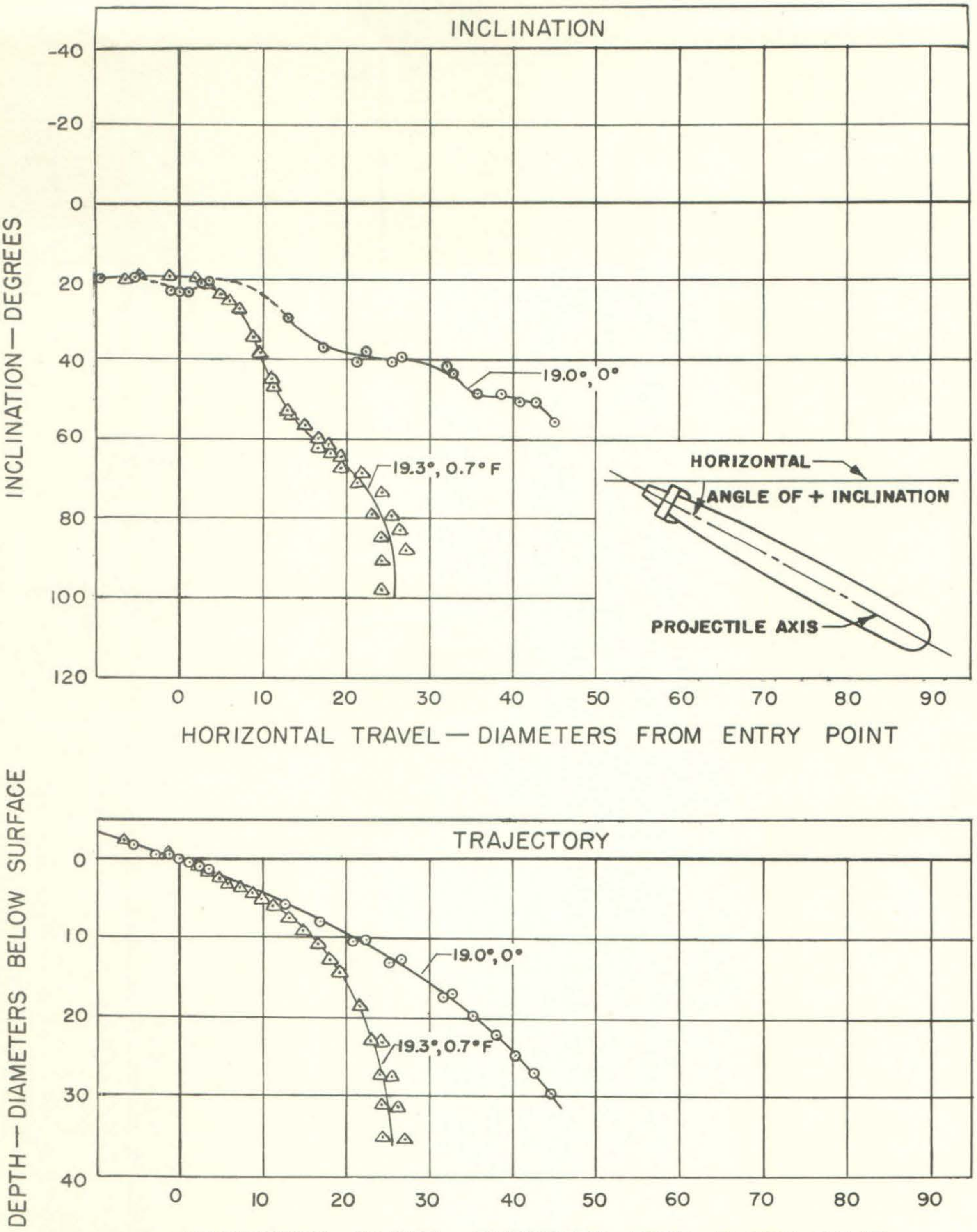
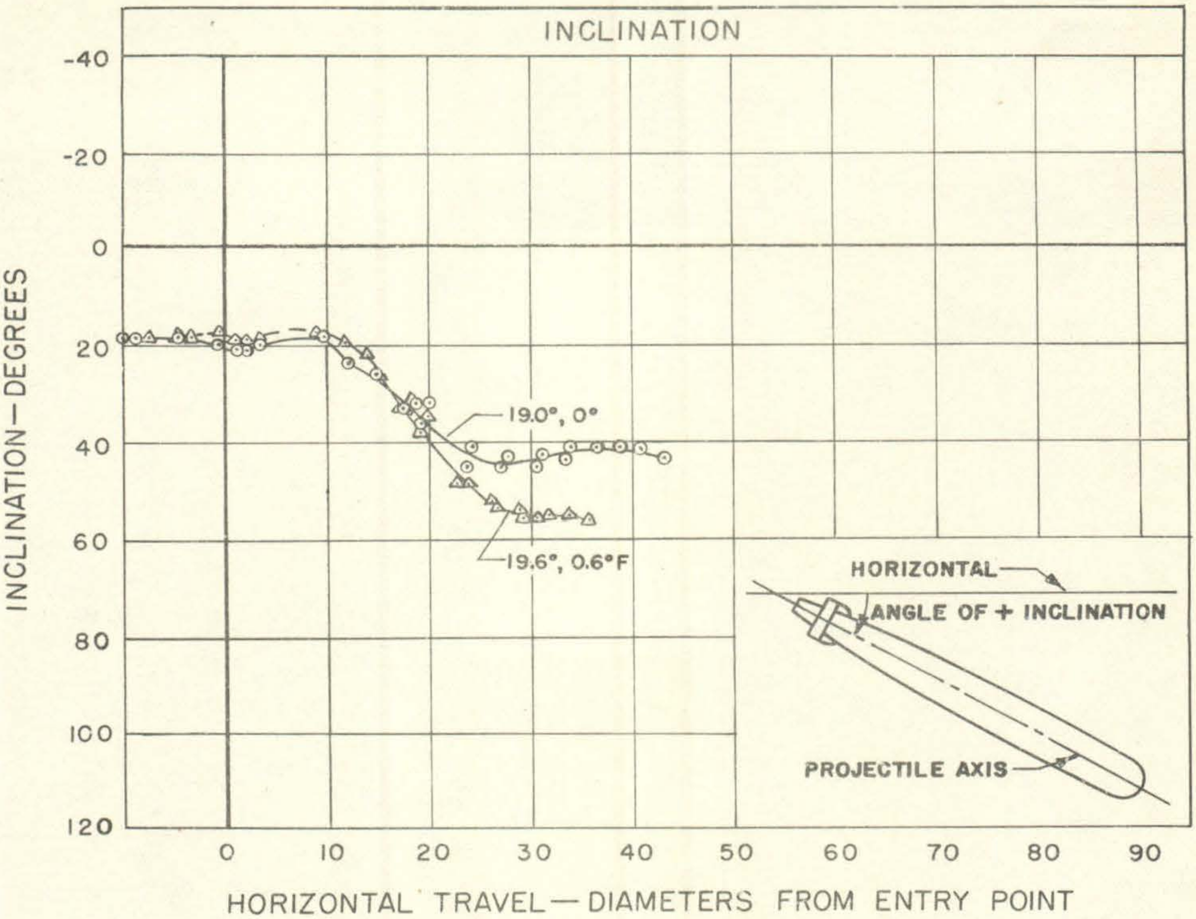


FIG. 11 - MK 13-6 TORPEDO WITH HEAD I
INDIVIDUAL MODEL TRAJECTORY AND INCLINATION CURVES
AIR PRESSURE 3/4 ATMOSPHERE



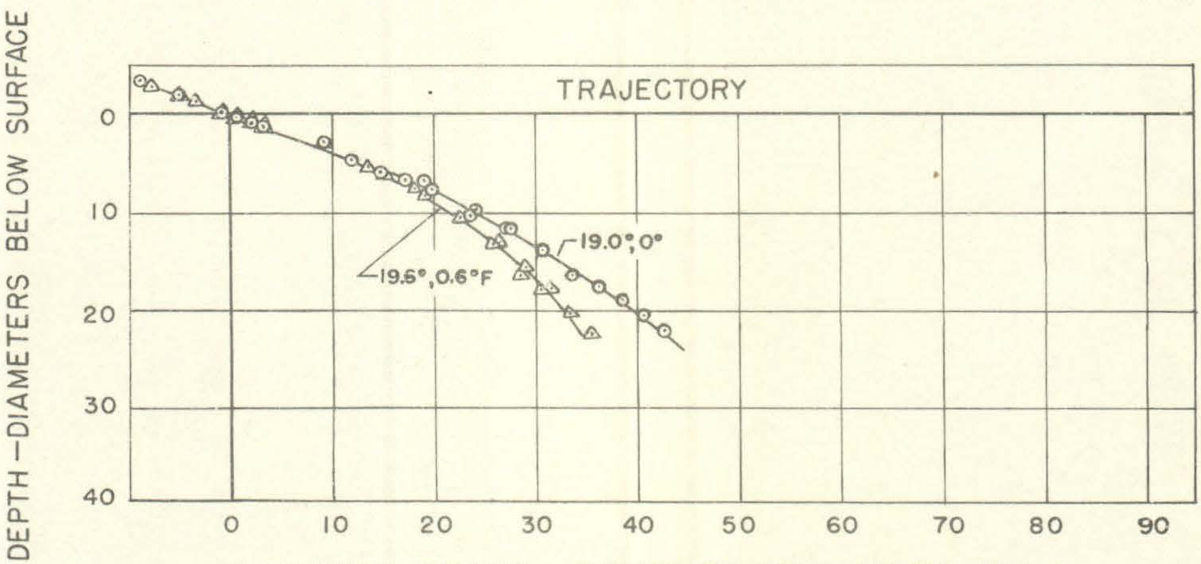


FIG. 12 – MK 13-6 TORPEDO WITH HEAD I
INDIVIDUAL MODEL TRAJECTORY AND INCLINATION CURVES
AIR PRESSURE 1/2 ATMOSPHERE

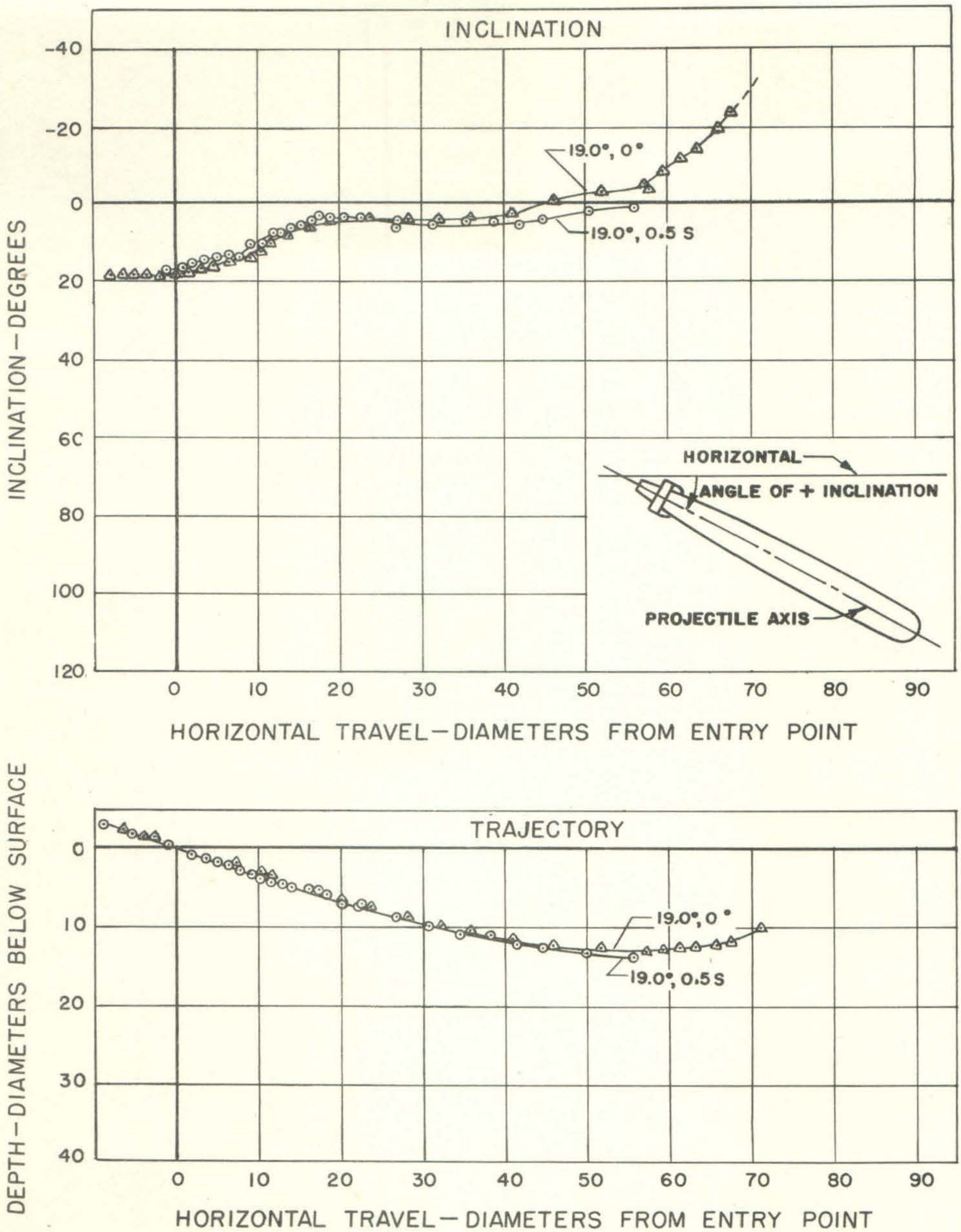


FIG. 13 - MK 13-6 TORPEDO WITH HEAD I
INDIVIDUAL MODEL TRAJECTORY AND INCLINATION CURVES
AIR PRESSURE 1/4 ATMOSPHERE

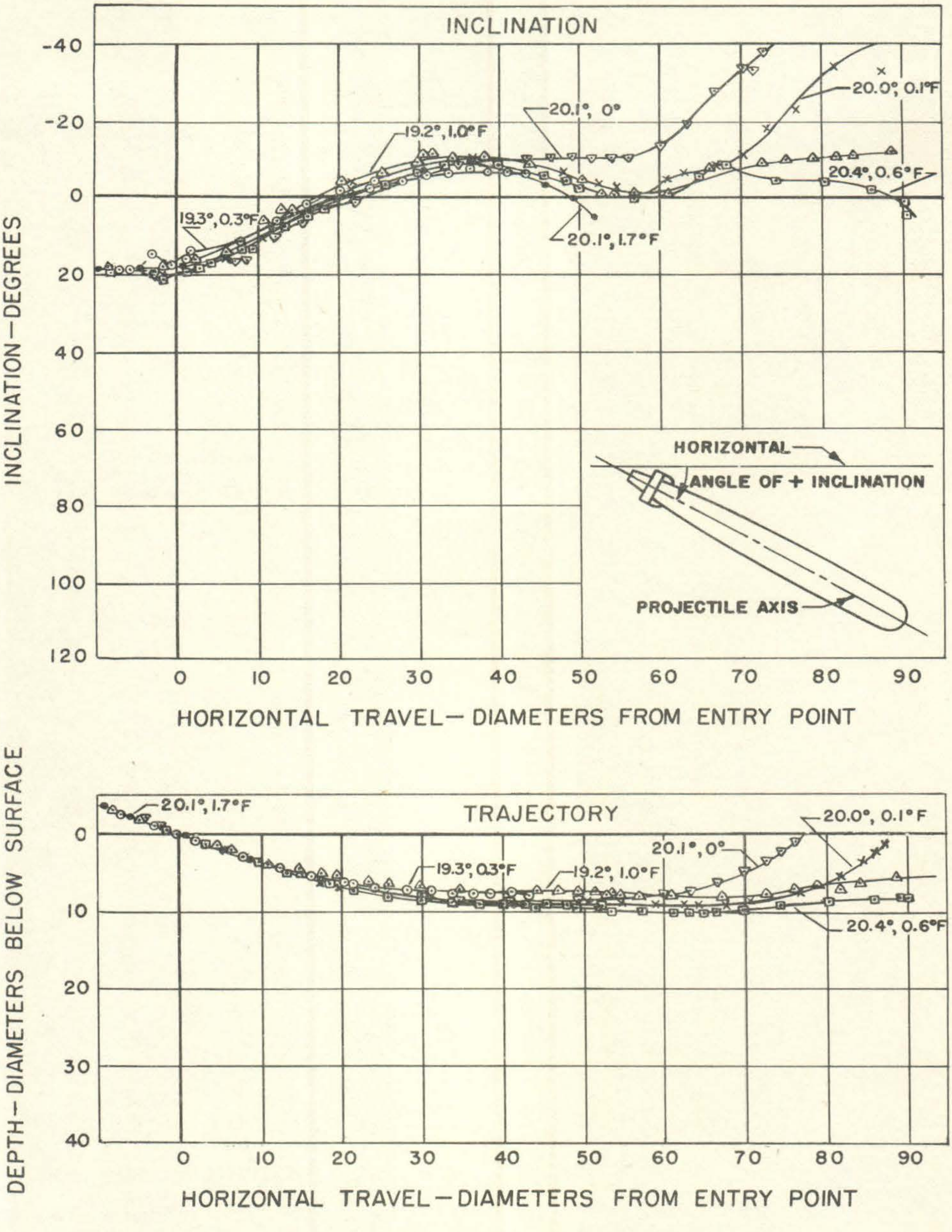


FIG. 14 – MK 13-6 TORPEDO WITH HEAD I
INDIVIDUAL MODEL TRAJECTORY AND INCLINATION CURVES
AIR PRESSURE 1/11 ATMOSPHERE

Although the two launchings made at 3/4 atmosphere, Figure 11, produced differing trajectories, no further investigations were made at this condition. It will be noted that the trajectory and pitch values were a bit different for the two runs. The use of this pressure condition was merely to establish the trend of an average trajectory as the tank air pressure was varied. The same considerations apply to the curves at 1/2 atmosphere in Figure 12 in which the divergence is smaller.

How closely data can be reproduced some of the time is illustrated in Figure 13, which shows results of launchings made at 1/4 atmosphere. One run is indistinguishable from the other for 50 diameters of horizontal travel. In this instance, as in some others, the length of trajectory recorded in one launching differs from another. This is the result of difficulties in conducting the tests, such as loss of the film record in one of the cameras.

Six launchings were made at the condition of major interest. This is the condition of 1/11 atmosphere, which is the theoretically correct pressure. The individual curves are presented in Figure 14. The launchings were made with two models. One model was damaged when it broached on its first run. It produced the earliest broaching trajectory. Whereas the other model produced consistently flat trajectories to 70 diameters of horizontal travel, this one started its upward travel with only a short length of flat trajectory. The data for the second model show no spread greater than 2 diameters for 75 diameters of horizontal travel. All trajectories show a spread no greater than 5 diameters out to a distance of 70 diameters of horizontal travel. This virtual duplication of trajectories is also interesting because the launchings represent a range of entry trajectory angles from 19.2° to 20.4° and entry pitch angles from 0° to 1.7° flat.

The comparison between the model trajectories at 1/11 atmosphere and the prototype trajectory is made in Figure 15. The prototype trajectory is approximated to within 2 diameters throughout its full length by the earliest broaching model trajectory. It is approximated to within 5 diameters by all trajectories to 70 diameters of horizontal travel.

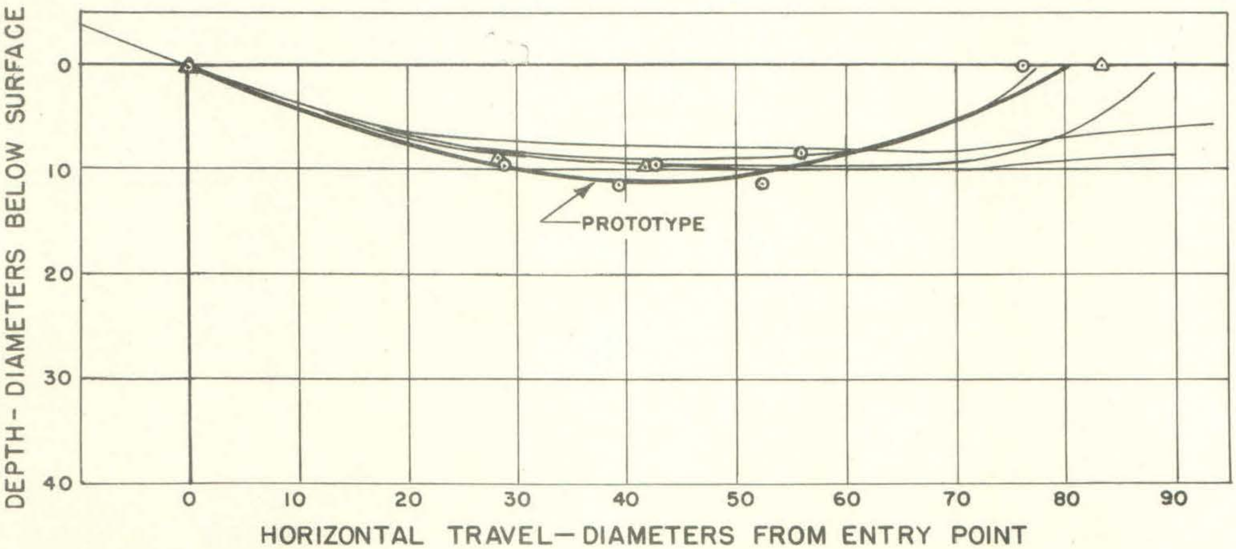
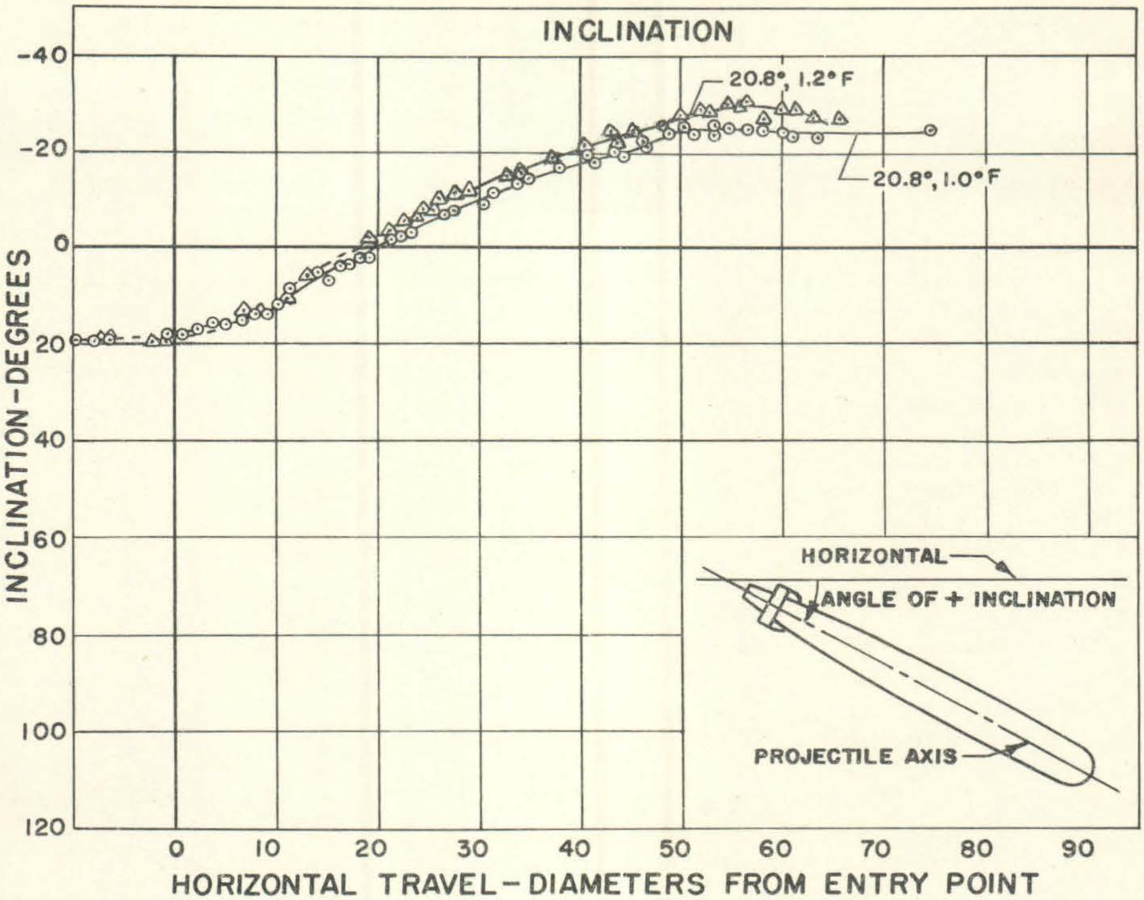


FIG. 15 – MK 13-6 TORPEDO WITH HEAD I
COMPARISON OF INDIVIDUAL MODEL TRAJECTORIES AT 1/11 ATMOSPHERE
WITH PROTOTYPE TRAJECTORY (POINTS SHOWN ARE FROM PROTOTYPE TESTS)



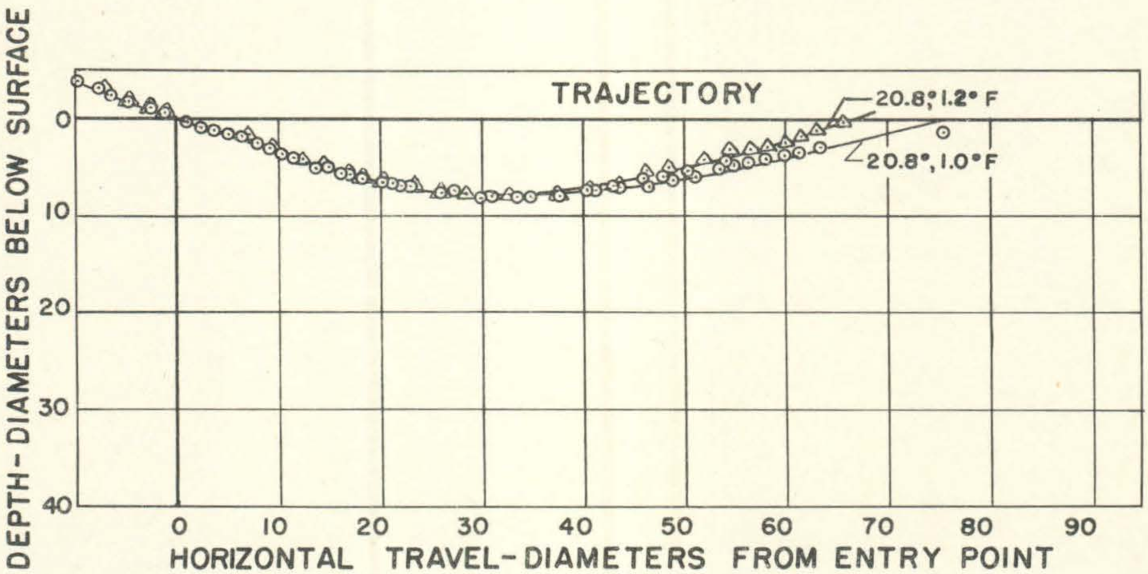


FIG. 16.— MK 13-6 TORPEDO WITH HEAD I
INDIVIDUAL MODEL TRAJECTORY AND INCLINATION CURVES
AIR PRESSURE 1/22 ATMOSPHERE

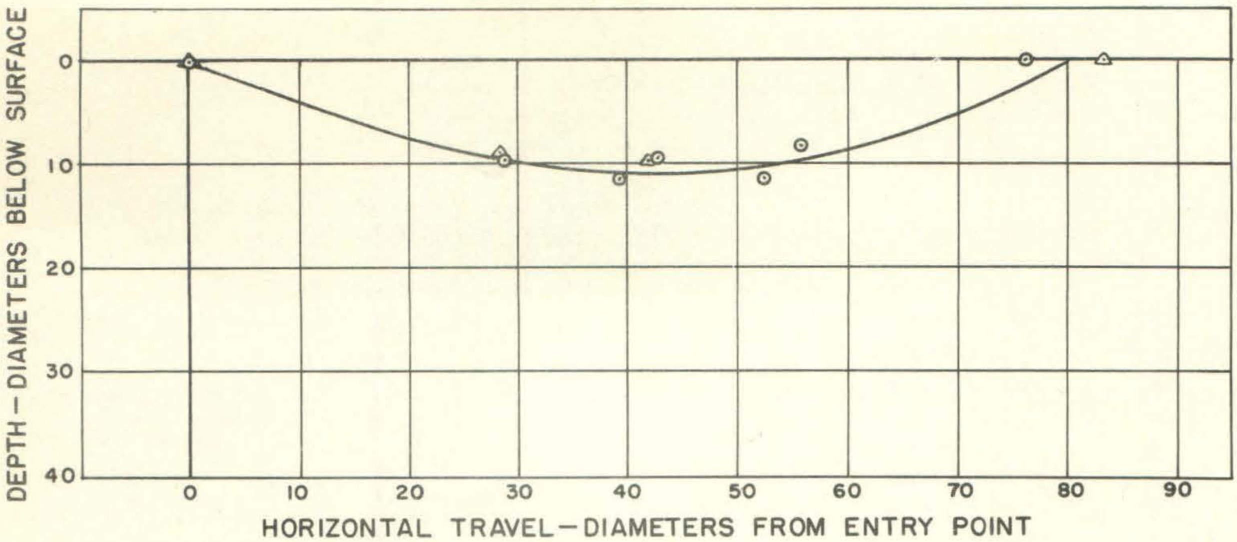


FIG. 17 - MK 13-6 TORPEDO WITH HEAD I
AVERAGE TRAJECTORY AND TEST POINTS FOR TWO PROTOTYPE RUNS
ENTRY SPEED 400 FPS

The two prototype test runs which were used to obtain the average prototype curve are shown in Figure 17. It is seen that at 55 diameters of horizontal travel the vertical spread between the test points is about 3.5 diameters.

These results indicate that, for the projectile and entry conditions used in these tests, reasonable similitude is obtained between the trajectory of the prototype and the trajectory of small models launhhed at Froude-scaled speed and atmospheric pressure scaled according to the linear scale of the model.

The data of two launchings at 1/22 atmosphere are shown in Figure 16. The trajectories show that the model has no tendency to run horizontally. The model broached in both runs. It is seen that a reduction in atmospheric pressure below the theoretically correct value causes the model trajectory to shift away from the prototype trajectory toward a faster recovery and broach (see Figure 8).

Turning from inspection of the trajectories to a consideration of the curves of inclination, it is seen that there is a specific inclination curve corresponding to each trajectory. Similar trajectories are associated with similar curves of inclination. The pattern of inclination values is different for each pressure condition. The differences between the curves of inclination at one pressure are seen to be even more pronounced than the differences between trajectories. A more detailed study of inclination and pitch angles may become a fruitful source of information on projectile behavior.

No detailed study has been made so far of the inclination curves, nor have values of the trajectory angle and pitch angle been determined except at the entry point, since the emphasis in this work has been upon a study of trajectories.

Head F

The tests with the 2-inch model of the MK 13-6 Torpedo with the standard head were made some months ago and were reported in a memorandum report[7]. The results are included in this report for comparison with the Head I tests, mainly to point out the great difference in sensitivity of the two shapes to variations in atmospheric pressure.

In Figure 18 are shown the trajectories resulting from three sets of duplicate launchings made at air pressures of 1, 1/2, and 1/22 atmosphere. For all these tests the entry angle was 19°, the initial pitch angle 0.8° flat, and the entry velocity was 103 ft. per sec. corresponding to a prototype velocity of 343 ft. per sec.

It is seen that the spread between any two trajectories at the same pressure is nowhere greater than one diameter, and that the spread of all six trajectories is not greater than about 2 diameters. It will be noted, also, that there seems to be a reversal in trend in that in going from 1 atmosphere to 1/2 atmosphere the trajectories are lowered, whereas a further reduction of pressure to 1/22 atmosphere causes the trajectories to rise again. Additional tests with this shape are now in progress to investigate this behavior in greater detail. These tests, made at an entry speed of 120 ft. per sec., also show this reversal in trend.

The insensitivity of this shape to variations in atmospheric pressure is very striking when compared to the great sensitivity of Head I, since the difference between the contours of the two nose shapes is not very great, as may be seen in Figure 3.

The prototype trajectory, shown in Figure 18, is an average trajectory for 16 launchings taken from Figure 9 (27) of reference 8. It is seen that all model trajectories come within two diameters of vertical displacement from the prototype trajectory. This is in agreement with the findings of other experimenters who obtained good similarity to prototype trajectory with small unvented models of the MK 13-6 Torpedo with standard head when launched with Froude-scaled entry velocity and without scaling atmospheric pressure. (Reference 1). It is interesting that there is almost perfect agreement between the prototype trajectory and the two model trajectories taken at 1/22 atmosphere. Among the three pressures used in these tests, the 1/22 atmosphere is nearest to the theoretically correct pressure of 1/11 atmosphere. This could be a fortuitous coincidence. On the other hand, it is possible that with this nose shape even small differences between trajectories are significant. Only further investigation can settle this point.

Reproducibility of Trajectories

In addition to the difference between the sensitivities of the two nose shapes to variations in atmospheric pressure, there is also a marked difference in the reproducibility of trajectories resulting from repeated launchings under the same conditions. With Head F, the same initial conditions produce trajectories that are alike to within one diameter. With Head I, on the other hand, reproducibility is good under low atmospheric pressure, but at higher atmospheric pressures there is considerable spread between trajectories resulting from supposedly identical initial conditions. At present only a tentative explanation can be offered for this difference in reproducibility.

As was indicated earlier in this report, in the case of Head F the flow in the cavity stage separates cleanly from the body and stays clear of the body until the projectile changes orientation in the cavity so that the tail comes in contact with the cavity wall. However, with the finer shaped Head I, when small models are launched

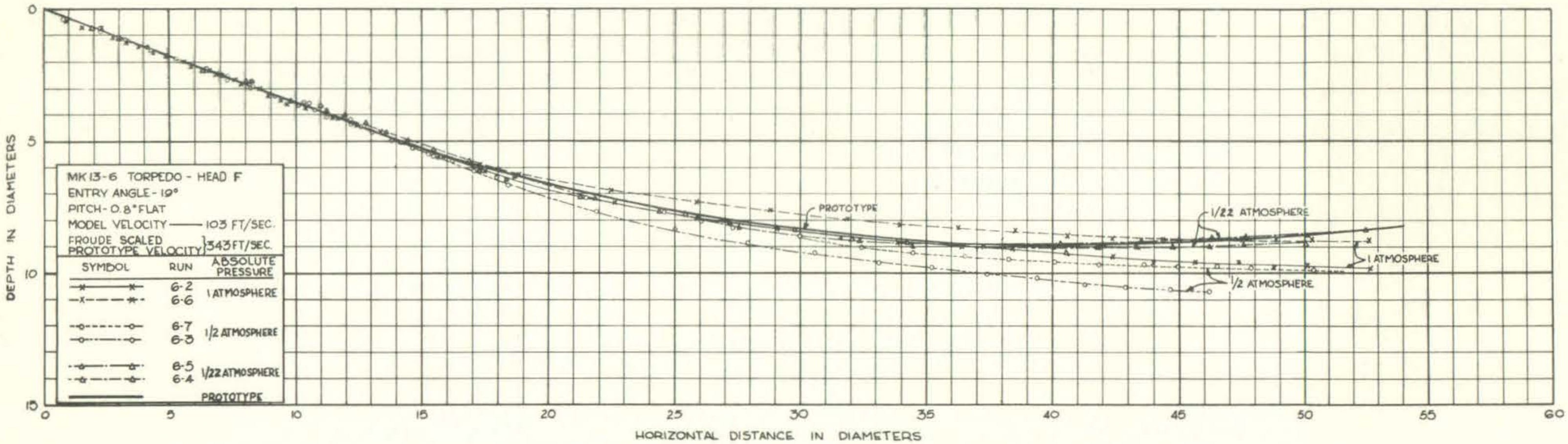


FIG. 13 – MK 13-6 TORPEDO WITH HEAD F

MODEL TRAJECTORIES AT VARIOUS ATMOSPHERIC PRESSURES COMPARED WITH PROTOTYPE TRAJECTORY

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under full atmospheric pressure, the flow does not stay clear of the body. The high velocity flow of water along the cavity wall pumps out the air in the narrow space between cavity and model on the underside of the nose. This creates an under-pressure and sucks the underside of the cavity in towards the model so that the water clings to the model (see Plate 14 of Reference 1). This transition from separated flow to clinging flow, like many other sudden transitions from one flow regime to another, is probably somewhat unpredictable. That is, very small and so far unmeasurable differences between one test run and another may "trigger" this transition and cause the time of its occurrence to differ slightly from run to run. These slight differences may be in water surface configuration due to ripples, or in model surface conditions such as surface finish or oiliness.

The same suction force that causes the change in the flow pattern also pulls the model nose downward and causes the model to dive. It is possible, therefore, that the time of occurrence of this transition is important enough to bias the remainder of the trajectory and to produce appreciable differences. This may explain why, with Head I under air pressure between half atmosphere and a full atmosphere, there is considerable spread between trajectories from the same entry conditions. At air pressures of 1/4 atmosphere or less, variations in air pressure within the cavity could not be very significant, and reproducibility of trajectories is improved.

Two models were used in the group of eight tests made at a pressure of one atmosphere. Seven of these show good agreement among themselves and the eighth deviated from the remainder. Five of the seven tests were made with one model and two with the other. This indicates that the manufacturing tolerances are close enough for the behavior of one model to be indistinguishable from that of another. The one deviating trajectory was the first run of a newly painted model, the same one with which the other five runs were later made. Another newly painted model, launched at 1/11 atmosphere, also produced a trajectory which differed from the others in that group. It appears, therefore, that, at least for projectiles with noses of fine shape, the surface finish may have a noticeable effect on entry behavior.

CONCLUSION

The detailed conclusions concerning the effect of atmospheric pressure on the entry behavior of the two shapes tested are given in the abstract at the beginning of this report. The following paragraphs contain a more generalized statement of the conclusions, and suggestions for further investigation.

1. The entry behavior of streamlined projectiles with fine nose shapes (such as the MK 13-6 Torpedo with Head I) cannot be simulated by small models launched under full atmospheric pressure even though the speed is correctly scaled according to Froude's law.

2. The entry behavior of fine-nosed projectiles can be simulated by small models (at least within the range of conditions covered by these tests) if the velocity is scaled according to Froude's law and the atmospheric pressure is scaled in proportion to the linear dimensions.

3. Analysis shows that in order to model some of the phenomena accompanying water entry, such as surface closure, it is necessary to maintain the density of the atmosphere used in model tests equal to that of the prototype. Since the pressure of the atmosphere in the case of the model should be lower than that

of the prototype, this requirement indicates the use of an atmosphere of heavy gas in model tests. The tests reported herein show that in the case of the oblique entry of elongated projectiles, this requirement does not have to be fulfilled, i.e., an air atmosphere may be used in model tests and the atmospheric density may be allowed to vary linearly with the pressure. From this it may be inferred either that surface closure does not occur, or that it occurs late and does not affect the subsequent behavior of the projectile.

4. The entry behavior of projectiles with sphere-typed heads (e.g., Head F) entering with pitch angles of one degree or less is only very slightly affected by atmospheric pressure. From this it may be inferred that model tests may be made at any atmospheric pressure. However, this is probably true only for a limited range of conditions.

Further investigation is necessary to determine the limits of applicability of these modeling laws. It is known, for instance, that small models of the MK 13-6 Torpedo with Head F launched under full atmospheric pressure and with various pitch angles have a critical pitch angle that is different from that of the prototype. The critical pitch angle is the value of the steep (nose down) pitch at which the behavior of the projectile changes abruptly from the upturning trajectory resulting from flatter pitch angles to a down-turning trajectory resulting from steeper pitch. The Launching Tank is now engaged in another series of tests to determine whether the critical pitch angle can be reproduced by models launched with Froude scaled velocity and with atmospheric pressure reduced in proportion to the linear dimensions. It is felt that an affirmative answer to this question, added to the results of the present tests, would justify considerable confidence in this procedure for modeling water entry phenomena.

Another important aspect of the problem yet to be investigated is that of modeling whip, i.e., the rapid change in angular velocity following nose impact. This is one of the most important factors in determining the water entry behavior of elongated projectiles. Indirect evidence on this point will be obtained from the critical pitch study now in progress, but this problem deserves more detailed examination.

Information on the whip characteristics of various nose shapes, combined with data on the forces acting on projectile components during the cavity stage, would form the basis for quantitative analysis and fairly reliable prediction of the entry behavior of projectiles. A study of the forces acting on projectile components during the cavity stage is now in progress in the Free Surface Water Tunnel of this laboratory.

APPENDIX I

THE CONTROLLED ATMOSPHERE LAUNCHING TANK

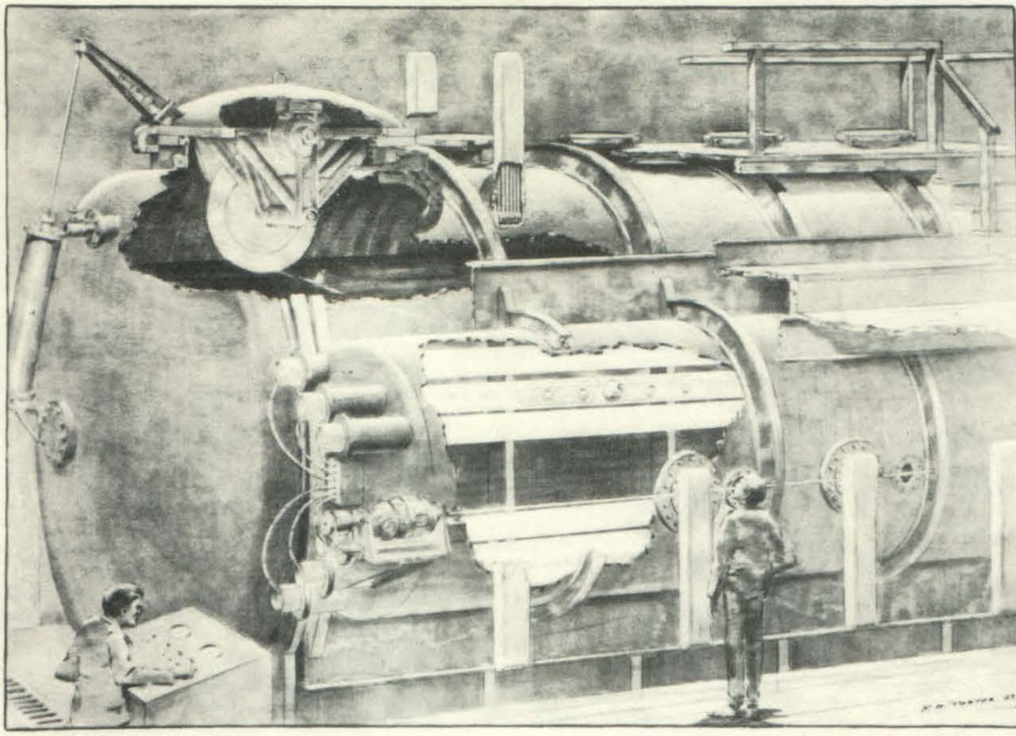
The Controlled Atmosphere Launching Tank was designed primarily for the study of the hydrodynamic factors involved when a body traveling freely through a gas, such as air, strikes a water surface and enters the water. Since it is sometimes necessary to control the gas pressure and density when studying hydrodynamic phenomena occurring at a surface between a gas and a liquid, the tank is a closed pressure vessel. It can also be used for other studies requiring similar equipment, such as explosions under water.

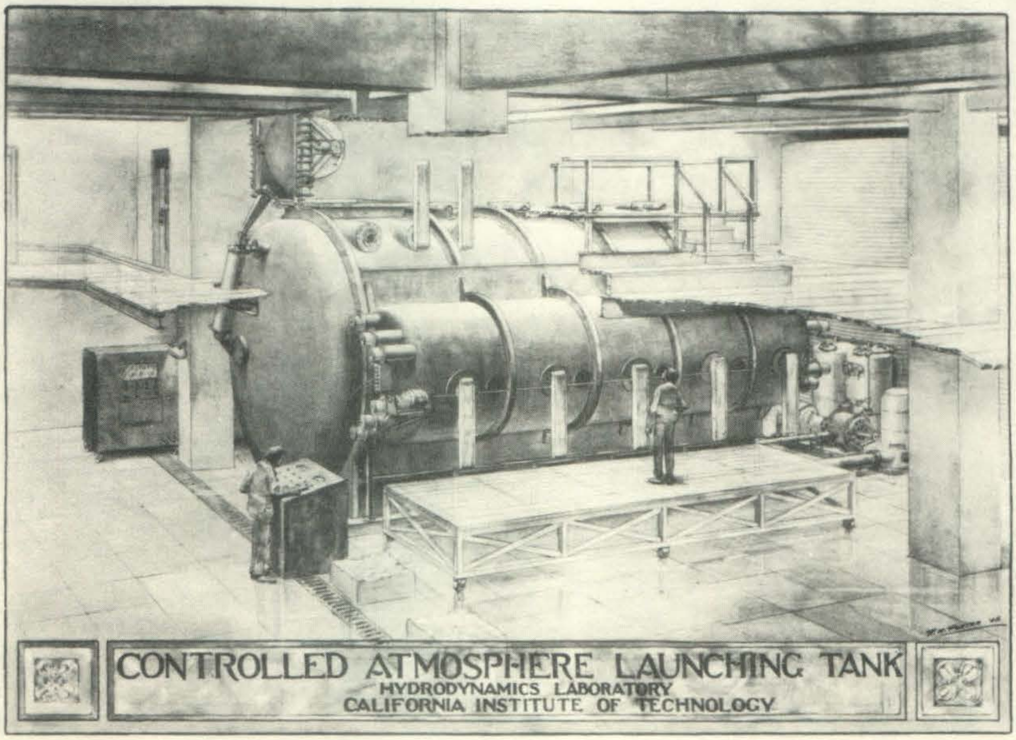
The tank is a cylinder of welded steel construction, 13 feet in diameter and 30 feet long. To one side of it is attached a section of a smaller cylinder for mounting some of the recording apparatus. In normal operation, the tank is filled with water to a depth of about 10 feet. A launching wheel is mounted on the underside of a large hatch cover on top of the tank. A device for holding a test model is located on this wheel. By adjusting the speed of rotation of the wheel, the model can be launched centrifugally at any desired speed up to 250 ft. per sec. The path of the model at the instant of launching can be adjusted to any angle between horizontal and vertical. The angle of the model with respect to the selected path can be adjusted to any angle up to ± 10 degrees.

The path of the model through the gas above the surface of the water and under water is recorded by two groups of high-speed 35mm motion picture cameras operated at constant speed by a synchronous motor. The requirements of the necessary high-speed photography ruled out conventional methods in which the interior of the tank would be illuminated continuously and light admitted intermittently to the film by means of a shutter. The cameras have no shutters. Exposures are made by intermittent illumination of the interior of the tank with special (Edgerton type) flash lamps. The number of exposures can be varied from 500 to 3000 per second. The light flash duration is about one-millionth of a second. The fields of view of adjacent cameras overlap to such an extent that the model is photographed by at least two of them during each exposure. This makes it possible to reproduce the path of the model by stereoscopic observation of the projected images. The film is spliced to form one continuous loop in each camera magazine. In operation, the camera shaft is accelerated slowly to prevent film breakage.

The flash lamps for photographing the underwater trajectory are housed in lucite tubes located in the bulge which also carries the underwater trajectory cameras.

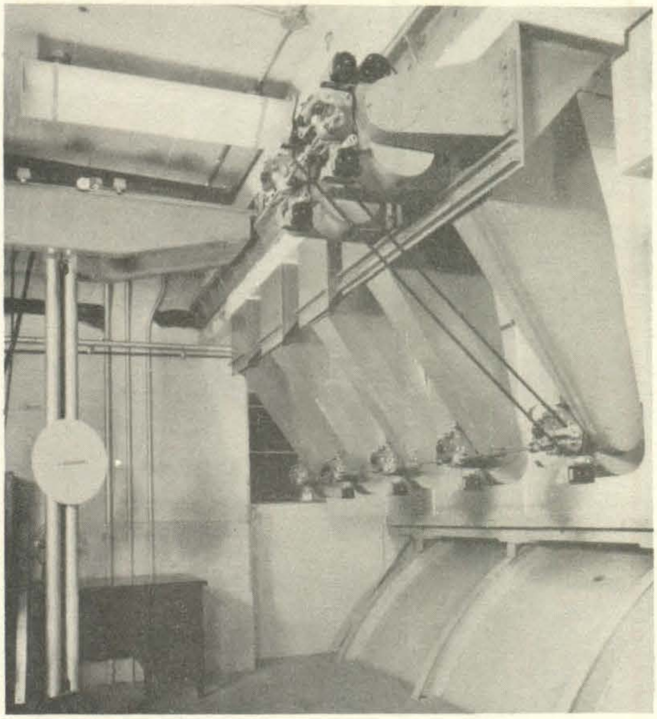
The tank is lined with a polyvinyl chloride plastic to prevent corrosion products from fouling the water. It is equipped with ultraviolet lamps to inhibit bacterial growth and with a filtration system to remove suspended matter from the water. These precautions are necessary because the underwater light path for photography is about 24 feet




CONTROLLED ATMOSPHERE LAUNCHING TANK
HYDRODYNAMICS LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

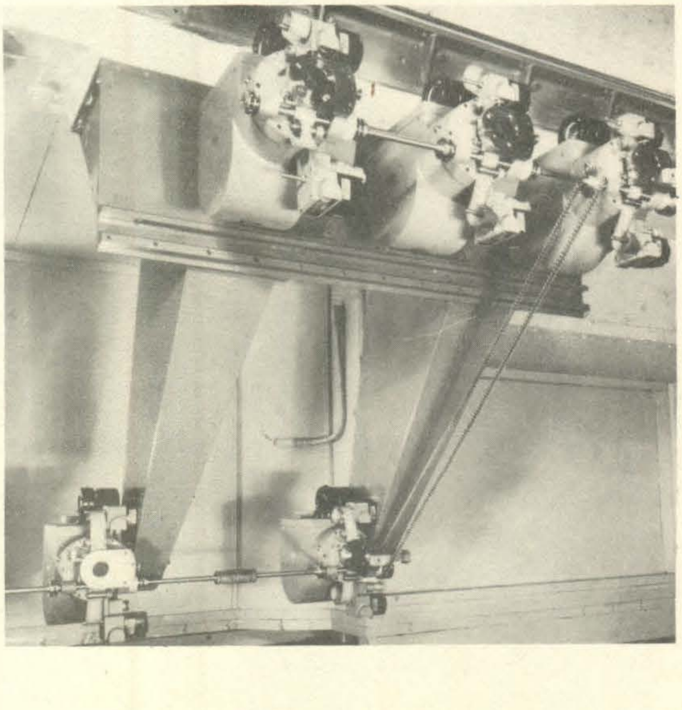
THE TRAJECTORY ANALYZER

THE trajectory analyzer is a device for reconstructing the path of a model from the high-speed motion picture records obtained at the Controlled Atmosphere Launching Tank. It provides information on the three linear and two angular components of position.

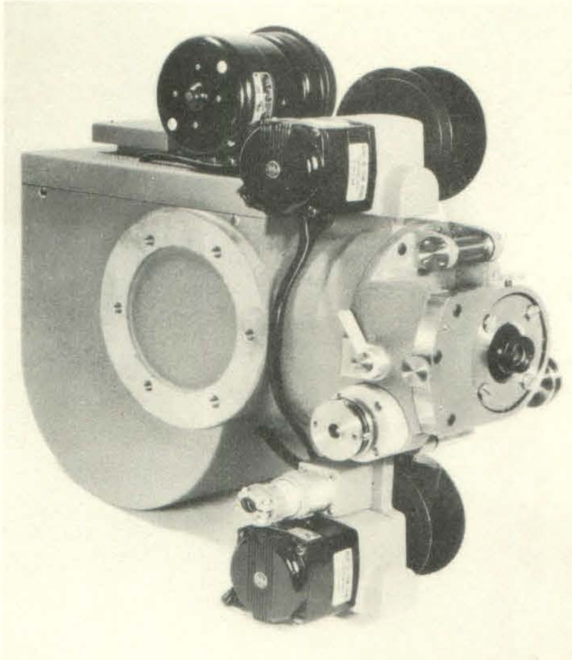


The analyzer is essentially a half-size reproduction of the recording system with projectors taking the place of cameras and a half model on a screen replacing the model. The screen is supported in such a way that it can be moved to any position and orientation to correspond to any model inclination. These components of motion are indicated by counters which supply the trajectory data for further analysis.

All of the films from one run in the launching tank are placed in the corresponding projectors with the film strips synchronized so that all frames taken simultaneously will be projected simultaneously. A common drive operates all projectors so that once the film strips are sunchronized, they remain so during the projection of the entire run. An image of the model is projected by at least two adjacent projectors. For each frame the sereen is maneuvered until both images fall on it. Additional maneuvering causes the images to fuse into one. The counter readings give the position and orientation of the model.



Each projector is equipped with a lens matched with the corresponding camera lens. The gate mechanism holds the film exactly in the focal plane. Temperature changes in the projector are kept low by use of low light intensity, a water cell between the light and the condensers, and an individual cooling fan.



APPENDIX II

SPECIFICATIONS FOR PRECISION MK 13-6 MODELS

	1"	2"	4.2"	8"	22.42"
Length Ratio = L $1/L$ $\sqrt{L}$ $1/\sqrt{L}$	1 1 1 1	2 .50000 1.4142 .7071	4.2 .23810 2.0494 .4879	8 .125000 2.8284 .3536	22.42 .04460 4.7343 .2112
Scale Factor = S $1/S$ $\sqrt{S}$ $1/\sqrt{S}$	22.4200 .04460 4.7350 .21119	11.2100 .08921 3.3481 .29868	5.3381 .18733 2.3104 .43283	2.8025 .35682 1.1740 .59736	1 1 1 1
Diameter	1 in. ±0.0013	2 in. ±0.0027	4.2 in. ±0.0056	8 in. ±0.01	22.42 in. ±0.030
Length*	7.079 in. ±0.04	14.16 in. ±0.08	29.73 in. ±0.19	56.63 in. ± 3/8	158.7 in. ±1
Total Weight	.1349 lb ±0.0013	1.079 lb ±0.01	9.995 lb ±0.096	69.07 lb ±0.68	1,520 lb. ±15
Fresh Water Displacement	.1541 lb. ±0.0013	1.233 lb ±0.01	11.42 lb ±0.096	78.90 lb ±0.68	1,737 lb ±15
Buoyancy	.0192 lb ±0.0025	.154 lb ±0.02	1.43 lb ±0.2	9.83 lb ±1.36	217 lb ±30
Distance of c.g. from Nose*	3.089 in. 0.020	6.178 in. ±0.04	12.97 in. ±0.09	24.71 in. ±0.18	69.25 in. ±0.50
Distance of c.b. from Nose*	3.117 in. ±0.02	6.234 in. ±0.04	13.09 in. ±0.09	24.94 in. ±0.18	69.88 in. ±0.50
Moment of Inertia about Transverse Axis thru c.g.	4.55×10^{-3} lb ft^2 $\pm 0.06 \times 10^{-3}$	.1455 lb ft^2 ±0.0018	5.93 lb ft^2 ±0.07	149.0 lb ft^2 ±1.9	2.57×10^4 lb ft^2 $\pm 0.03 \times 10^4$

* Measured from Tangent to Hemisphere

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DISTRIBUTION LIST

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